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# The Impact Of Upland Development And Marsh Width On Groundwater Composition In Estuarine Tidal Creeks In The Southeastern Coastal United States

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# The Impact of Upland Development and Marsh Width on Groundwater Composition in Estuarine Tidal Creeks in the Southeastern Coastal United States

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ABSTRACT

Coastal upland development has been shown to negatively impact surface water quality in tidal creeks along the southeastern coastal United States, but the impact of development on groundwater quality is not well understood. Increases in impervious cover associated with development has the potential to increase groundwater contamination as well as reduce fresh rainwater infiltration into the subsurface, which may decrease discharge of fresh groundwater to the estuary. We hypothesized that groundwater nutrient concentrations and salinity ranges would be higher in developed watersheds than in undeveloped watersheds.

Groundwater discharging from coastal uplands often travels through salt marshes before discharging to tidal creeks. Salt marshes export nutrients to tidal creeks, and significant mixing and transformation can occur during transport through the salty, highly-reducing sediments of a salt marsh. We hypothesized that the mixing and reactions in salt marshes may obscure the impacts of development on groundwater composition discharging to the creeks. To test these hypotheses, we sampled groundwater in the upland area and below the creek bank of 15 tidal creeks located within developed and undeveloped watersheds (measured by percent impervious cover) that exhibited a range of marsh widths. Sampling took place over two years, with Year 1 sampling occurring at all 15 creeks during the summer, and with Year 2 sampling occurring at a subset of 6 creeks (chosen based on accessibility) revisited for summer and winter sampling. Samples were analyzed for salinity, dissolved organic carbon, nitrogen and phosphorus concentrations.

Overall, significantly higher concentrations of nutrients were found in developed watersheds and lower concentrations of dissolved organic carbon were found in undeveloped watersheds. Concentrations of these constituents in groundwater sampled below the creek bank during Year 2 were often orders of magnitude higher than in groundwater sampled along the upland. No significant relationship was observed between land-use and salinity range. Significant relationships between marsh width and nutrient concentrations emerged at some individual creeks during Year 2 summer sampling. Seasonal differences in creek bank groundwater composition were observed. These differences may be related to lower mean sea levels during the winter season, during which time salt marshes may experience less tidally driven groundwater mixing in the sub-marsh aquifer. Results from this study will be used to improve best management practices of salt marsh tidal creeks along the southeastern coastal United States.

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# CHAPTER 1

# INTRODUCTION

In the United States, coastal counties account for approximately 10% of land area (excluding Alaska), yet contain 39% of the population (NOAA 2013). Between 1970 and 2010, the number of coastal residents increased by almost 40% and is projected to rise by an additional 10 million people by 2020 (Crosset et al. 2004, NOAA 2013). The area of developed land along the coast has been increasing rapidly at rates approximately six times the rate of population growth. The combination of condensed populations and the associated increases in impervious cover results in a magnification of the impacts of land development (Allen and Lu 2003, Beach 2002). Prior studies in tidal creeks located along the South Carolina coast have confirmed that the ultimate stressor on the ecosystem is human population density in the watershed, which is associated with increases in impervious cover (Holland et al. 2004). While previous work in the area (Holland et al. 2004, Sanger et al. 1999a, 1999b, 2015) has examined the relationship between development and surface water quality in tidal creeks, a similarly extensive study has not been performed examining the implications for groundwater quality. Salt marshes in tidal creeks are often viewed as a buffer between upland activity and the downstream environment. However, while the size of salt marshes is variable, the relationship in tidal creeks between marsh width and groundwater discharging along the creek banks has not been well studied. Understanding the impact of development on groundwater quality, as well as the effect of marsh width on groundwater composition, is critical to maintaining appropriate best management practices in coastal areas

## 1.1 GROUNDWATER FLOW TO TIDAL CREEKS

The primary controls on groundwater flow through tidal creeks (Figure 1.1) include groundwater originating from the upland, precipitation, evapotranspiration, tidal fluctuations, and the geometry and hydraulic properties of the marsh sediments (Wilson and Morris 2012). Salt marshes in the coastal southeastern US are characterized by a thin layer of Holocene sediment (silt, clay, fine sand and organic debris) over a Pleistocene sand base (Gardner 2007, Harvey et al. 1987, Hemond and Fifield 1982, Weigart & Freeman 1991). The conceptual stratigraphy for this project (Figure 1.2) is based on previous characterizations of salt marshes at North Inlet Estuary in Georgetown, SC and at Cabretta Island in Brunswick, GA (Carter et al. 2008, Wilson et al. 2011, Wilson et al. 2015). Transects from these studies revealed a mud or mixed mud layer about 1 m thick overlying a confined sand aquifer. The sand aquifer is typically 1-2 orders of magnitude more permeable than the mud layer (Wilson and Morris 2012). The sand aquifer provides a hydraulic connection between the fresh groundwater originating in the upland and surface water derived from the creek, where mixing between the different sources can occur in a dynamic, spatially fluctuating ecotone designated as the hyporheic zone (Gardner 2004, Wilson et al. 2011).

Of the factors that control groundwater flow in salt marshes, tidal input is the most important driver for groundwater exchange (Wilson and Morris, 2012). Twice-daily, semi-diurnal tides flood and drain the salt marshes, resulting in a continued mixing of surface water and groundwater. Tidally driven groundwater exchange occurs in the sub-marsh aquifer zone, with the mixed source groundwater then discharging to the creek. The largest volume of groundwater discharge from salt marsh sediments occurs at low tide, at or near the intersection of the creek bank and the creek water surface (Gardner 2005, Gardner 2007, Wilson and Morris 2012). This groundwater discharge is greatly enriched in nutrients compared to surface water (Gardner 2004, Whiting and Childers 1989, Wilson and Morris 2012).

Tidal creeks in South Carolina are mesotidal systems, with an average tidal range of about 1.4 – 2.6 m (NOAA 2018). Elevation and flooding frequency divide the marsh into high and low zones, with the low marsh flooding daily and the high marsh flooding during spring (bi-monthly high) tides and storms. Evidence of the influence of tides is seen in the abundance of *Spartina alterniflora*, a smooth cord grass that has evolved to withstand saltwater and which dominates the low marsh. At high spring tides, *Spartina* is almost totally submerged; at low tides, the sediment is exposed (Weigart & Freeman 1991, Wilson and Gardner 2006, Wilson et al. 2015).

### 1.2 IMPACT OF DEVELOPMENT ON HYDROLOGY

Tidal creeks act as an important hydrologic link between estuaries and land activities (Sanger et al. 2015). Developing forested upland (Figure 1.1) and replacing it with impervious cover limits the ability of rainfall to infiltrate into the subsurface, reducing the overall volume of rainfall infiltration and resulting in an increase in surface runoff (Holland et al. 2004). Urban development can thus divert rainwater to limited flow points, bypassing important natural soil and vegetation buffers (Woodward and Wui

2001). A general rule exists that when more than 10% of the acreage of a watershed is covered in impervious surfaces, the streams and rivers located within the ecosystem become seriously degraded. The ecosystems become less diverse, less stable and less productive than those located in natural watersheds (Beach 2002). Increases in watershed development have also been shown to correlate positively with increases in nutrient loads and salinity ranges in tidal creek surface water, with the larges fluctuations in salinity occurring in creeks located in developed watersheds (Holland et al. 1997, Holland et a. 2004, Sanger et al. 1999a, Sanger et al. 2015).

## 1.3 SALINITY

Controls on salinity are similar to those on groundwater flow and include evapotranspiration, precipitation, tidal influence and runoff. In South Carolina, evapotranspiration and precipitation are typically highest in the summer and lowest in the winter (Arguez et al. 2010, Trewartha 1981). Prior studies have observed corresponding seasonal fluctuations in salinity, with average salinities in the marsh basin highest in the summer and lowest during the winter (Carter et al. 2008; Goni and Gardner 2003). Along the creek bank, tidal exchange and freshwater input have the strongest influence on groundwater salinity. Twice daily tides flood and drain the marsh, resulting in groundwater-surface water mixing. Watershed development decreases the volume of freshwater infiltration in the upland, increases the volume of runoff, and has been shown to correspond with larger salinity ranges in tidal creek surface water (Sanger et al. 2015). Seasonal sensitivity of groundwater in tidal creek salt marshes may also be impacted by mean elevation of the creek relative to mean sea level, which is higher in the summer and lower in the winter (Wilson et al. 2015). Depending on the geometry of the creek system, the marsh area may be inundated more frequently during the summer season than during the winter, effecting the biogeochemical processes in the marsh.

The size of the upland and marsh areas also influence the volume of fresh water input and the level of mixing that occurs. Upland width relates to the volume of fresh groundwater available to discharge to a tidal creek, as wider uplands present a greater area for recharge to occur. Marsh width, measured as the distance from the creek bank to the forest-marsh boundary (Figure 1.2), relates to the usefulness of marshes to mitigate groundwater contamination arriving from the upland (Gardner et al. 2007). This project aims to evaluate the influence of upland development on the quality of groundwater input to tidal creeks and to assess the effects of salt marsh width on groundwater composition.

## 1.4 NUTRIENT AND CARBON CYCLING IN SALT MARSH SYSTEMS

Assessing nutrient and carbon composition in groundwater in salt marsh tidal creeks is complicated by seasonal and tidal forces, spatial heterogeneity and anthropogenic impacts. Seasonal changes, including those impacting salinity and mean sea level, alter important controls on groundwater composition. Twice daily tides result in groundwater-surface water mixing and tidal flushing of groundwater. Marsh and basin heterogeneity and varying levels of upland development further complicate measurements. Previous studies examining the role of groundwater input in estuarine environments have observed a net advection of nutrients from marshes to tidal creeks (Wilson and Morris 2012), and have shown nutrient concentration and speciation to vary with development and salinity (Hutchins et al. 2014, Jun et al. 2013, Sanger et al. 2015), but few have examined specifically how these factors affect groundwater composition at multiple tidal creeks. This study aims to assess salt marsh tidal creek groundwater composition while considering the confounding effects of watershed development and seasonal variability.

*NITROGEN*

Nitrogen is the limiting nutrient in most coastal ecosystems and is an important factor in controlling primary production and promoting eutrophication of coastal waters (Altman 2012, Redfield 1985). Salt marshes may act as a source or sink of nitrogen depending on the microbe mediated nitrogen fixation and denitrification processes (Viers et al. 2012). Nitrogen is present in the atmosphere as highly stable dinitrogen ($N_2$), and through the process of nitrogen fixation is transformed into ammonia ($NH_3^+$) followed by rapid conversion to ammonium ($NH_4^+$). The ammonium may adsorb to negatively charged particles (such as clay), be used by plants or microbes, or be transformed into nitrite/nitrate ($NO_2^-$/$NO_3^-$), before ultimately returning to the atmosphere as dinitrogen. Nitrogen enters groundwater at varying concentrations and in varying forms. Nitrate, which does not significantly adhere to or react with sediments, moves with groundwater flow; while ammonia, which is subject to sorption, rapidly converts to nitrate under oxidizing conditions. Dissolved organic nitrogen concentrations are also generally lower than nitrate concentrations, due to the high adsorption levels (Viers et al. 2012). In fresh surface water and fresh groundwater, inorganic nitrogen may appear in the form of nitrate, nitrite or ammonia, while in saline groundwater inorganic nitrogen appears dominantly as ammonia (Hutchins et al. 2014).

Additionally, the growth and decay cycle of *Spartina alterniflora* may have a seasonal influence on groundwater nitrogen concentrations, as the plants uptake ammonium during the summer growth period (Howes et al 1985a, Howes and Geohringer 1994, Valiela et al. 1976, Yelverton and Hackney 1986). Development and salinity can also affect nitrogen concentration and speciation. Sanger et al. (2015) observed higher concentrations of total dissolved nitrogen (TDN) and ammonium in tidal creeks located in developed versus undeveloped watersheds, with higher levels in the shallow, narrow headwater sections of the creeks. Previous studies have also observed changes in phytoplankton community biomass in response to nutrient concentration and speciation (Garces et al. 2011, Hutchines et al. 2014, Paerl et al. 2003). Understanding the potential impacts of groundwater quality on phytoplankton communities will serve to inform best management practices of tidal creeks.

*PHOSPHORUS*

In coastal environments, phosphorus can enter wetlands via physical deposition of sediment and particulate organic phosphorus. Inorganic phosphorus in the form of the orthophosphate ion ($PO_4^{3-}$) also has a tendency to sorb to sediment particles. Sedimentation can result in significant input of phosphorus, but the sediment may become resuspended, and as a result sorption activities may be the mechanism more responsible for long-term phosphorus in wetlands (Bruland and Richardson 2004). Salinity is a key control on phosphorus sorption, as negatively charged ions in seawater may compete with orthophosphate ions for binding sites on the soil particles, effectively mobilizing them (Bruland and DeMent 2009, Junhong et al. 2017). Previous studies have shown that speciation may differ in fresh and saline groundwater, with sorption of phosphorus decreasing as salinity increases (Hutchins et al. 2014, Jun et al. 2013). Regarding sediment composition, Sanger et al. (1999a) found that developed watersheds may experience a higher load of iron (Fe), aluminum (Al), calcium (Ca), magnesium (Mg), and organic matter, which are able to sorb available phosphorus in wetland soils and thus may affect the concentration of phosphorus in groundwater. Orthophosphates are used by aquatic plants and can lead to eutrophication, and the input of orthophosphates may be increased by anthropogenic activities and upland development (Hutchins et al., 2014).

### *DISSOLVED ORGANIC CARBON*

Organic matter, measured as dissolved organic carbon (DOC), is an important factor in controlling geochemical processes in groundwater. DOC may result from allochthonous sources, such as leaves and other forest liter in the upland area, or from autochthonous sources, such as algae or vascular macrophytes (including *Spartina alterniflora*). DOC may influence the availability of nutrients and the mobility of metals and other contaminants (Aiken and Kuniansky2002). Previous studies have shown seasonally high summer and low winter DOC concentrations in groundwater discharging along a salt marsh creek bank, which relates to the growth and decay. This coincides with the growth of plant roots as well as the maximum rates of organic matter decay in salt marshes (Howes et al 1985a, Howes and Geohringer 1994, Valiela et al. 1976, Yelverton and Hackney 1986)

## 1.5 PURPOSE

The purpose of this project is to assess the impact of development and marsh width on groundwater composition in tidal creeks in the southeastern coastal United

States. This project was designed to test two major hypotheses regarding groundwater composition. First, we hypothesized that upland development would have a significant impact on the overall composition of groundwater both in the upland and along the creek bank. We further hypothesized that DOC concentrations would be highest in undeveloped watersheds, and that nutrient concentrations would be highest in developed watersheds. Second, we hypothesized that marsh width would have a significant impact on the composition of groundwater discharging along the creek bank, with concentrations of nutrients, DOC and salinity increasing with marsh width. To test these hypotheses we sampled at fifteen tidal creeks located in undeveloped (forested or suburban) and developed (urban) watersheds. Sampling took place over two years. Year 1 sampling occurred during the summer of 2016 at the fifteen creeks. Year 2 sampling occurred during the summer and winter of 2017-2018 at six of the original fifteen creeks. Fieldwork results were analyzed using linear regressions, one-way ANVOAs and Mann-Whitney U-tests, with the null hypothesis of each analysis being that there were no significant differences in groundwater composition due to upland development or marsh width.

Figure 1.1 A salt marsh/tidal creek system surrounded by forested upland (Wadmalaw Island, SC).

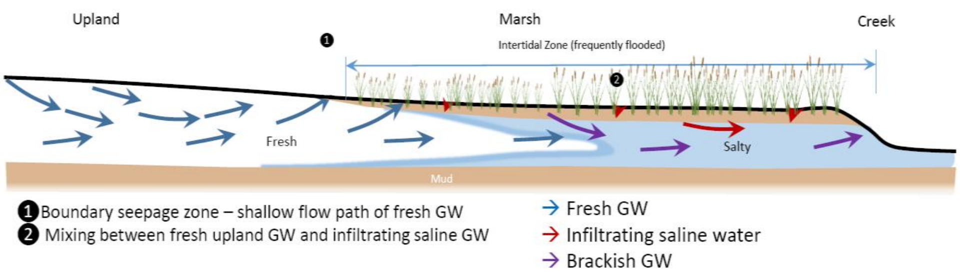


Figure 1.2 Groundwater conceptual flow model.

# CHAPTER 2

# METHODS

## 2.1 LAND-USE CATEGORIES

Land-use and impervious cover for each watershed were previously determined by Sanger et al. (2015) using ArcGIS 9. They classified each watershed based on the level of impervious cover, including forested (<10 % impervious cover), suburban (≥10 % but <35 % impervious cover), and urban (≥35 % impervious cover). We used those categories for our fifteen tidal creeks during Year 1, choosing creeks from five forested, five suburban, and five urban watersheds. For the six tidal creeks sampled during Year 2, watersheds were categorized as either undeveloped (forested, <10 % impervious cover) or developed (suburban and urban, ≥10% impervious cover), resulting in three undeveloped and three developed watersheds. This simplified classification system is supported by prior studies which showed that streams and rivers begin to become seriously degraded when more than 10% of a watershed is covered in impervious cover (Beach 2002, Hutchins et al. 2014, Holland et al. 2004, Larson and Belovsky 2013, Sanger et al. 2015). Limiting the number of creeks during Year 2 allowed us to develop a more manageable sampling plan and to perform seasonal sampling, while still maintaining statistical integrity.

## 2.2 SAMPLE COLLECTION AND ANALYSIS

Groundwater samples were collected from below the creek bank and in the adjacent uplands. Sampling points during Year 1 were located on either side of the creek and stretched along the length of the tidal creeks. The goals during Year 1 were to sample a wide range of marsh widths and gain a better understanding of the composition of groundwater discharging along the creek banks. Marsh widths were measured using ARCGIS 10, as the distance from the creek bank to the forest-marsh boundary and ranged from 0-124 m (Figure 2.1). Sampling during the first year typically began during rising low or rising mid tide, with a goal of sampling in a sand layer at a depth of 1-1.5 m below the sediment-water interface. Stratigraphic variation (i.e. a thicker or thinner overlying mud layer) led to variations in sampling depths. To reduce uncontrolled variables that may have been confounding results during Year 1, in Year 2 sampling points were restricted to a single stretch of the creek bank within each creek (Figure 2.1). Sampling was also restricted to begin within thirty minutes of low rising tide, when groundwater discharge is highest (Whiting and Childers 1989, Wilson and Morris 2012). Sampling took an average of 2-3 hours (depending on creek size and ease of sampling). Sampling depths ranged from 0.5-1.8 m, with an average depth of 1.3 m.

For Year 2 sampling, three creeks in undeveloped watersheds and three creeks in developed watersheds were chosen from the original fifteen creeks. Groundwater sampling in the upland adjacent to the creek banks was also added during Year 2. Large uplands (>1500 m) were chosen at each creek for consistency. Crab Haul Creek, Guerin Creek and Village Creek were selected as the creeks in undeveloped watersheds and Okatie Creek, Bulls Creek and Shem Creek were selected as the creeks in developed watersheds (Table 2.2). However, we found that we could not sample in the upland at Guerin Creek or at Okatie Creek, as the push-point and peristaltic pump were unable to pull groundwater from the upper 2 m of soil. To address this, we sampled in the uplands of Long Creek and Parrot Creek, located in undeveloped and developed watersheds respectively. Upland samples for all six creeks were collected along a 50 m transect landward of and parallel to the upper margin of the Juncus zone, with a sample taken every 10 m. Upland sampling took an average of 20 minutes and points were sampled at an average depth of approximately 1.6 m.

Groundwater samples were collected using a peristaltic pump and a stainless steel push-point. Samples were field-filtered using EMD Millipore 0.45 GF/F filters and transported on ice in the dark and either refrigerated at 4 $^{o}$C (for DOC and salinity) or frozen at -80 $^{o}$C (for nutrients) until analysis.

## 2.3 ANALYTICAL METHODS

Salinity was measured using a handheld conductivity probe. Total dissolved nitrogen (TDN) was measured using a Technicon II autoanalyzer following persulfate oxidation (Gilbert and Loder 1977). A modified version of the phenylhypochlorite method of Solarzano (1969) was used to determine dissolved ammonium ($NH4^{+}$) concentrations, taken as the total concentration of dissolved inorganic nitrogen ($NH4^{+}$) Total dissolved phosphorus (TDP) was measured spectrophotometrically (Koroleff 1983) following a high temperature combustion method of (Monaghan and Ruttenberg 1999). Dissolved inorganic phosphorus (DIP) was quantified as soluble reactive phosphorus (SRP), determined spectrophotometrically using standard molybdate blue colorimetric methods (Koroleff 1983). Dissolved organic nitrogen and phosphorus (DON and DOP) were estimated by subtracting $NH4^+$ from TDN and SRP from TDP, respectively. Filtrate aliquots of 10 mL were immediately acidified to pH < 2 with 10% HCL and stored in the dark at 4 $^{o}C$ until analyzed for DOC via a Shimadzu TOC-VCPN organic carbon analyzer following Benner and Strom (1993).

## 2.4 STATISTICAL ANALYSIS

One-way ANOVAs, Mann-Whitney U tests, and linear regressions were performed to analyze differences in groundwater quality due to watershed type, marsh width, and seasonal variability. An alpha value (i.e. the probability of rejecting the null hypothesis when the null hypothesis is true) of 0.05 was used for all statistical analysis.

### *ONE-WAY ANOVAS*

One-way ANOVAs of Year 1 summer creek bank groundwater was performed to analyze differences in average concentrations of water quality parameters (salinity, DOC, nutrients). Land-use class factors were forested (F), suburban (S) and urban (U). Parameters were either inverse- (salinity, TDN, DON) or ln-transformed (DOC, $NH4^+$, TDP, SRP, DOP) to satisfy normality assumptions. Transformations for TDP and DOP improved, but did not satisfy normality. Post-hoc multiple comparisons were performed using least squared means (Bonferroni Test).

### *MANN-WHITLEY U-TESTS*

Mann-Whitley U tests were performed on Year 2 summer/winter upland/creek bank groundwater. The ANOVAs performed for Year 1 samples were not appropriate for Year 2 samples, as Year 2 had only two groups (undeveloped, developed) where Year 1 had three (forested, suburban, urban), and ANOVAs require a minimum of three independent variables. While independent sample t-tests are a standard alternative to one-way ANOVAs when there are only two independent variables, they require data to satisfy normality assumptions. Transformations of Year 2 data often improved, but did not satisfy, assumptions of normality. Thus the non-parametric Mann-Whitney U test, which does not assume normality, was used to analyze Year 2 data.

*LINEAR REGRESSIONS*

Linear regression analyses for both Year 1 and Year 2 were performed to determine if there was a significant linear relationship between the dependent variable (marsh width, salinity) and the independent variable (water quality parameters) in creek bank groundwater.


Figure 2.1. A salt marsh/tidal creek system surrounded by suburban development in Okatie Creek, SC, where the width of the marsh (between the forest-marsh boundary and the creek bank) varies along a single marsh section. Point A shows a marsh width of 24 m and an upland of 5600 m; Point B shows a marsh width of 68 m and an upland width of 5600 m.

# CHAPTER 3

# RESULTS

Our sampling revealed significant variability in groundwater among different watershed types. Overall, higher concentrations of nutrients were found in the upland and along the creek bank of tidal creeks located in developed watersheds. Year 2 sampling revealed seasonal variability in groundwater composition, with higher average DOC concentrations found at four of the creeks sampled during the summer and higher average TDN concentrations found at five of the creeks sampled during the winter. Variability observed between creeks located within the same watershed type indicate that spatiotemporal factors that were not controlled for (e.g. marsh width, tidal window, watershed type) impact groundwater composition.  spatiotemporal heterogeneity

## 3.1 YEAR 1 SUMMER

Overall, Year 1 creek bank groundwater in suburban and urban watersheds was found to have higher concentrations of nutrients than that in forested watersheds. One-way ANOVAs of Year 1 summer creek bank groundwater revealed significantly lower concentrations of TDP and SRP in creeks located in forested versus suburban and urban watersheds (Figure 3.1; Table 3.1). However, these trends were not as pronounced as expected and there were no clear, significant trends observed between marsh width and groundwater quality (Appendix A.8). No significant differences in TDP or SRP concentrations were observed between the two developed watershed types, suburban and

and urban (Table 3.1). Each creek type also had large standard deviations for both TDP and SRP concentrations, indicating a degree of within watershed type variability (Table 3.2). As previously discussed in the Methods section, this variability led to the development of new sampling methods for Year 2 aimed at eliminating uncontrolled variables. With these changes, clearer trends emerged between marsh width and groundwater quality, and more significant differences were observed between groundwater in undeveloped versus developed watersheds. No clear trends emerged during Year 1 between salinity or salinity range and land-use category (Figure 3.2).

## 3.2 YEAR 2 SUMMER

### *YEAR 2 SUMMER UPLAND SAMPLES (MANN-WHITLEY U TESTS)*

Non-parametric Mann-Whitney U tests of Year 2 summer upland groundwater indicate that there were significant differences in DOC, $NH4^{+}$, DON and TDP concentrations in groundwater located in undeveloped versus developed watersheds (Table 3.3). Uplands in undeveloped watersheds had higher average DOC concentrations than those in developed watersheds (Appendix Table B.2). With the exception of DON, the average concentrations of all nutrients in upland groundwater during Year 2 summer was higher in undeveloped than in developed watersheds.

### *YEAR 2 SUMMER CREEK BANK SAMPLES (MANN-WHITLEY U TESTS)*

During Year 2 summer sampling, average concentrations of all nutrient constituents were higher in creek bank samples located in developed watersheds, sometimes by an order of magnitude or more (Table 3.4a,b). U-tests indicate significant differences for TDN, DON, and all phosphorus concentrations between watershed types

(Table 3.5a), with higher concentrations in developed watersheds. Overall, Bulls Creek had the highest concentrations of all nutrients (Table 3.4b).

Average DOC concentrations were similar at four of the six creeks (Village, Guerin, Okatie, and Shem) and ranged from 464-567 µmol/l. DOC concentrations were highest at Crab Haul Creek and Bulls Creek, with an average concentration of 707 µmol/l and 1329 µmol/l, respectively (Table 3.4a). Bulls Creek had unusually high concentrations of DOC (Table 3.4b); without Bulls Creek, the overall average DOC concentrations in the remaining developed creeks fell below the overall average at the undeveloped creeks. This suggests that while there were significant differences in DOC concentrations in upland groundwater samples, that trend is not always observed in groundwater discharging from the creek bank.

Salinity varied among the six creeks sampled during Year 2. Salinity values ranged from 1.33 ppt (Okatie Creek, undeveloped watershed) to 32.31 ppt (Crab Haul Creek, undeveloped watershed), with no clear relationship observed between salinity or salinity range and watershed type (Table 3.4a, b). It is interesting to note that Bulls Creek and Guerin Creek, which had two of the lowest average salinities, are located relatively inland compared to the other creeks, which may be a factor in the low values. Considering the important of salinity in effecting other components of groundwater chemistry, this variability is an important factor.

*YEAR 2 SUMMER LINEAR REGRESSIONS*

When groundwater from creeks located in each watershed type were analyzed as a whole, there were no statistically significant relationships observed during Year 2 summer between marsh width or salinity and other water quality parameters (Table 3.6).

When analyzed based on watershed type, significant relationships emerged in creek bank groundwater in undeveloped watersheds (Table 3.6, Figure 3.5), with significant positive relationships observed between marsh width and salinity ($r^2$ = .48), TDP ($r^2$ = .52), and SRP ($r^2$ = .46). As discussed in the Introduction, phosphorus has a tendency to sorb to sediments and is generally immobile. Phosphorus sorption has been shown to decrease with increased salinity, and may be affected here by tidally driven mixing of saline water. For creeks where this trend was not observed, both marsh sediment and watershed type could be confounding factors resulting in variable sorption capacities at each site (Maron and Roberts, 2014).

The strongest linear relationships were observed within the individual creeks (Figure 3.4, Table 3.7a, 3.7b). At Crab Haul Creek, a positive linear relationship was observed between marsh width and salinity ($r^2$ =.51), TDP ($r^2$ =.51) and SRP ($r^2$ = .56). At Okatie Creek, a significant linear relationship was observed between marsh width and the majority of groundwater parameters including TDN ($r^2$ =.38), $NH4^+$ ($r^2$ = .26), DON ($r^2$ = .45), TDP ($r^2$ = .37) and DOP ($r^2$ = .60). Interestingly, the majority of the linear relationships between marsh width and water quality parameters at Okatie Creek were negative, while the majority of the relationships at the other six individual creeks were positive. Compared to the other two creeks located in undeveloped watersheds, the average nitrogen concentrations at Okatie Creek fell in between (Table 3.4b). Okatie Creek is located adjacent to a golf club, and it is possible that there are high inputs of nitrogen from activities along the golf course which are diluted further out into the creek. At Bulls Creek, a significant linear relationship was observed between marsh width and the dissolved organic nutrients, DON ($r^2$ = .71) and DOP ($r^2$ = .68). No significant linear relationships were observed between marsh width and water quality parameters at Village Creek, Guerin Creek or Shem Creek. The relatively low salinities at Guerin Creek and Shem Creek may in part explain the weak relationships observed. Bulls Creek again appears to be an outlier, as it had a similarly low average salinity of 10.03 ppt while still exhibiting some significant relationships in regards to marsh width. Results from this study at Bulls Creek suggest that it is an outlier (i.e. very high concentrations of water quality parameters, observed variations in stratigraphy) among the creeks selected. However Village Creek, with an average salinity of 15.20 ppt and which appeared to fit the stratigraphy of the conceptual model, did not exhibit any significant relationships between marsh width and groundwater composition. This variability between creeks located within the same watershed reflects the level of heterogeneity that may be present at each creek (e.g. creek system geometry, sediment type) that was not controlled for.

## 3.3 YEAR 2 WINTER

Moving into winter, significant seasonal differences in DOC upland groundwater concentrations were observed in both watershed types, with higher concentrations found in undeveloped uplands during the summer and in developed uplands during the winter. No significant seasonal differences were observed in nitrogen upland groundwater concentrations (Table 3.3b).

For all creek bank groundwater samples, significant seasonal differences were observed in average DOC concentrations, with average Year 2 winter creek bank DOC concentrations higher than summer averages at four of the sample creeks (Figure 3.5, Table 3.3b). A significant seasonal difference in average TDN concentrations creek bank groundwater was observed only at Crab Haul Creek and Okatie Creek. With the exception of Okatie Creek, average TDN concentrations were higher at all creeks during winter (Figure 3.5, Table 3.4, Appendix B.3). As discussed in the Introduction, the growth and decay cycle of *Spartina alterniflora* could be related to the observed seasonal variations in DOC and nitrogen. However, this relationship is not consistent; sampling at a larger selection of creeks would help to elucidate if there was a true relationship. While significant seasonal differences in phosphorus concentrations were observed only at undeveloped creeks, overall average TDP concentrations were higher during the winter at all the majority of the creeks (Table 3.3, Table 3.4, Appendix B.3).

Significant differences in salinity between Year 2 summer and winter creek bank samples were observed at two of the lower salinity creeks, Guerin Creek (undeveloped) and Shem Creek (developed). Average winter salinity values at both creeks were approximately double those in the summer (Table 3.4, Appendix Table B.3), which may be related to regionally higher levels of precipitation during the summer.

Interestingly, while during Year 2 summer the strongest relationships between marsh width and water quality parameters were observed at individual creeks, during Year 2 winter many of these trends disappeared, and the strongest relationships were observed when the three creeks located in undeveloped watersheds (Crab Haul Creek, Village Creek, Guerin Creek) were analyzed together (Table 3.7, Appendix A.11). A drop in mean sea level during the winter could be contributing to the weakened relationships between marsh width and groundwater composition at the individual creeks. Lower mean sea levels during the winter could result in less tidal flooding of the marshes and therefore less mixing and tidally driven groundwater exchange.

Table 3.1. One-way ANOVA of Year 1 summer creek bank groundwater analyzing differences in average concentrations of water quality parameters (salinity, DOC, nutrients); significant values ($p < 0.05$ are bolded; post-hoc model factors (arranged from low to high) with different superscripts are statistically different.

| Creek bank Parameter | ANOVA | | |
|---|---|---|---|
| | F | p-value | Post-hoc |
| InverseSalinity (ppt) | (F(2,80) = 0.608 | .55 | N/A |
| lnDOC (μmol/l) | F(2,79) = 0.276 | .76 | N/A |
| InverseTDN (μmol/l) | (F(2,80) = 0.841 | .44 | N/A |
| $\ln NH4^{+}$ (μmol/l) | F(2,82) = 1.719 | .19 | N/A |
| InverseDON (μmol/l) | F(2,79) = 0.591 | .56 | N/A |
| *lnTDP (μmol/l) | F(2,82) = 6.959 | **.002** | $F^{a}$ $S^{b}$ $U^{b}$ |
| lnSRP (μmol/l) | F(2,81) = 4.864 | **.01** | $F^{a}$ $S^{b}$ $U^{b}$ |
| *lnDOP (μmol/l) | F(2,78) = 1.056 | .35 | N/A |

Table 3.2 Year 1 summer creek bank groundwater sample descriptive results for salinity, DOC, nitrogen, and phosphorus.

| | Forested | | | | Suburban | | | | Urban | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | N | Min | Max | Mean (Std. Dev) | N | Min | Max | Mean (Std. Dev) | N | Min | Max | Mean (Std. Dev) |
| Salinity (ppt) | 19 | 14.17 | 31.3 | 22.42 (5.82) | 31 | 0.06 | 31.2 | 16.14 (9.61) | 29 | 0.08 | 30 | 16.21 (9.27) |
| DOC (µmol/l) | 19 | 237 | 1210 | 520 (241) | 31 | 38 | 1098 | 530 (236) | 29 | 133 | 1777 | 636 (498) |
| TDN (µmol/l) | 19 | 14 | 278 | 99 (78) | 31 | 5 | 429 | 115 (122) | 29 | 7 | 1203 | 283 (322) |
| NH4$^+$ (µmol/l) | 19 | 3 | 206 | 69 (68) | 31 | 4 | 334 | 77 (99) | 29 | 2 | 458 | 122 (138) |
| DON (µmol/l) | 19 | 0 | 73 | 34 (19) | 31 | 0 | 141 | 37 (30) | 29 | 5 | 1172 | 160 (281) |
| TDP (µmol/l) | 19 | 2 | 45 | 14 (13) | 31 | 2 | 143 | 31 (29) | 29 | 3 | 192 | 49 (60) |
| SRP (µmol/l) | 19 | 1 | 62 | 17 (17) | 31 | 2 | 147 | 33 (32) | 29 | 1 | 197 | 45 (53) |
| DOP (µmol/l) | 19 | 0 | 3 | 0 (1) | 31 | 0 | 11 | 1 (3) | 29 | 0 | 67 | 5 (16) |

Table 3.3 Mann-Whitney U tests for Year 2 upland groundwater analyzed by (a) season in undeveloped vs. developed watersheds and by (b) watershed type in summer vs. winter sampling; significant values ($p < 0 05$) are indicated in bold; note that not enough data points were available for analysis of SRP or DOP winter samples.

(a)

| Upland Parameter | Year 2 Summer Undeveloped vs. Developed | | | Year 2 Winter Undeveloped vs. Developed | | |
|---|---|---|---|---|---|---|
| | M-W U | N | p-value | M-W U | N | p-value |
| DOC (µmol/l) | 45.0 | 29 | **.01** | 27.0 | 26 | **.003** |
| TDN (µmol/l) | 92.0 | 29 | .60 | 37.0 | 26 | **.02** |
| $NH4^+$ (µmol/l) | 61.0 | 29 | .06 | 44.0 | 26 | **.047** |
| DON (µmol/l) | 42.0 | 29 | **.01** | 30.0 | 26 | **.01** |
| TDP (µmol/l) | 44.5 | 28 | **.01** | 75.0 | 26 | 0.72 |
| SRP (µmol/l) | 79.0 | 28 | .40 | N/A | N/A | N/A |
| DOP (µmol/l) | 68.5 | 28 | .18 | N/A | N/A | N/A |

(b)

| Upland Parameter | Year 2 All Summer vs. Winter | | | Year 2 Undeveloped Summer vs. Winter | | | Year 2 Developed Summer vs. Winter | | |
|---|---|---|---|---|---|---|---|---|---|
| | M-W U | N | p-value | M-W U | N | p-value | M-W U | N | p-value |
| DOC (µmol/l) | 220.0 | 55 | **.01** | 29.0 | 30 | **< .001** | 42.0 | 25 | .06 |
| TDN (µmol/l) | 343.0 | 55 | .57 | 71.0 | 30 | .09 | 37.0 | 25 | **.03** |
| $NH4^+$ (µmol/l) | 342.0 | 55 | .56 | 52.0 | 30 | **.01** | 34.0 | 25 | **.02** |
| DON (µmol/l) | 278.0 | 55 | .10 | 58.0 | 30 | **.02** | 45.0 | 25 | .09 |
| TDP (µmol/l) | 315.0 | 54 | .40 | 78.0 | 29 | .25 | 70.0 | 25 | .73 |
| SRP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| DOP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table 3.4 Year 2 summer creek bank groundwater descriptive results for DOC, nitrogen, and phosphorus concentrations for individual creeks in (a) undeveloped and (b) developed watersheds.

(a)

| | Crab Haul Creek | | | Village Creek | | | Guerin Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) |
| Salinity (ppt) | 12.6 | 32.3 | 23.2 (6.85) | 2.10 | 22.3 | 15.2 (8.63) | 8.00 | 9.80 | 8.88 (0.06) |
| DOC (µmol/l) | 308 | 1275 | 707 (321) | 126 | 837 | 464 (234) | 374 | 812 | 523 (202) |
| TDN (µmol/l) | 62 | 286 | 128 (59) | 23 | 196 | 95 (64) | 23 | 158 | 81 (67) |
| NH4$^{+}$ (µmol/l) | 39 | 172 | 92 (45) | 18 | 145 | 69 (53) | 11 | 126 | 63 (59) |
| DON (µmol/l) | 0 | 11 | 1 (3) | 0 | 8 | 1 (3) | 0.00 | 1 | 0.2 (0.3) |
| TDP (µmol/l) | 0.02 | 25 | 11 (8) | 7 | 32 | 19 (10) | 3 | 20 | 8 (8) |
| SRP (µmol/l) | 13 | 32 | 23 (7) | 2 | 22 | 15 (8) | 8 | 10 | 9 (1) |
| DOP (µmol/l) | 0 | 11 | 1 (3) | 0 | 8 | 1.4 (3) | 0 | 0.7 | 0.2 (0.3) |

(b).

| | Okatie Creek | | | Bulls Creek | | | Shem Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) |
| Salinity (ppt) | 1.33 | 29.53 | 23 (10) | 8.8 | 11.7 | 10.03 (1.06) | 8.6 | 11 | 9.46 (1.05) |
| DOC (µmol/l) | 49 | 969 | 566 | 784 | 2056 | 1329 (410) | 221 | 633 | 459 (170) |
| TDN (µmol/l) | 45 | 1002 | 382 (328) | 55 | 1649 | 586 (759) | 105 | 375 | 259 (132) |
| NH4$^{+}$ (µmol/l) | 43 | 412 | 192 (125) | 33.1 | 982 | 302 (348) | 79 | 161 | 105 (34) |
| DON (µmol/l) | 0 | 77 | 22 (25) | 0.78 | 217 | 73 (80) | 0 | 17 | 9 (6) |
| TDP (µmol/l) | 18 | 57 | 37 (13) | 69.25 | 135 | 93 (24) | 9 | 43 | 29 (134) |
| SRP (µmol/l) | 1 | 30 | 23 (10) | 9 | 12 | 10 (1) | 9 | 11 | 9 (1) |
| DOP (µmol/l) | 0 | 77 | 22 (25) | 1 | 217 | 73 (80) | 0 | 17 | 9 (6) |

Table 3.5 Mann-Whitney U tests for Year 2 creek bank groundwater analyzed by (a) season in undeveloped vs. developed watersheds and by (b) watershed type in summer vs. winter sampling; significant values ($p < 0.05$) are indicated in bold.

(a)

| Groundwater Parameter | Year 2 Summer Undeveloped vs. Developed | | | Year 2 Winter Undeveloped vs. Developed | | |
|---|---|---|---|---|---|---|
| | M-W U | N | p-value | M-W U | N | p-value |
| Salinity (ppt) | 126.5 | 34 | .85 | 163.0 | 39 | .48 |
| DOC (µmol/l) | 132.0 | 34 | 1.0 | 174.0 | 39 | .69 |
| TDN (µmol/l) | 84.0 | 34 | .09 | 76.0 | 39 | **.001** |
| $NH4^+$ (µmol/l) | 99.0 | 34 | .25 | 77.0 | 39 | **.001** |
| DON (µmol/l) | 71.0 | 34 | **.03** | 96.0 | 39 | **.008** |
| TDP (µmol/l) | 32.0 | 32 | **.01** | 146.0 | 39 | .23 |
| SRP (µmol/l) | 22.0 | 32 | **<.001** | N/A | N/A | N/A |
| DOP (µmol/l) | 78.0 | 32 | .20 | N/A | N/A | N/A |

(b)

| Groundwater Parameter | Year 2 All Summer vs. Winter | | | Year 2 Undeveloped Summer vs. Winter | | | Year 2 Developed Summer vs. Winter | | |
|---|---|---|---|---|---|---|---|---|---|
| | M-W U | N | p-value | M-W U | N | p-value | M-W U | N | p-value |
| Salinity (ppt) | 441.0 | 73 | **.01** | 91.0 | 33 | .20 | 131.0 | 40 | .07 |
| DOC (µmol/l) | 530.0 | 73 | .14 | 87.0 | 33 | .15 | 173.0 | 40 | .51 |
| TDN (µmol/l) | 653.0 | 73 | .91 | 119.0 | 33 | .81 | 171.0 | 40 | .48 |
| $NH4^+$ (µmol/l) | 652.0 | 73 | .90 | 109.0 | 33 | .54 | 159.0 | 40 | .30 |
| DON (µmol/l) | 638.0 | 73 | .78 | 111.0 | 33 | .59 | 180.0 | 40 | .64 |
| TDP (µmol/l) | 574.0 | 71 | .56 | 40.0 | 31 | **.01** | 182.0 | 40 | .68 |
| SRP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| DOP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table 3.6 Linear regressions of Year 2 summer creek bank groundwater for marsh width against salinity, DOC, nitrogen, and phosphorus concentrations; relationships examined for all creeks, creeks in undeveloped and developed watersheds, and Bulls Creek (BC) and Shem Creek (SC) together; bold values indicate statistically significant ($p < 0.05$) relationships.

| | All Creeks | | | Undeveloped | | | Developed | | | Bulls Creek and Shem Creek | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | $r^2$ | p | Slope | $r^2$ | P | Slope | $r^2$ | p | Slope | $r^2$ | p | Slope |
| Salinity (ppt) | .08 | .05 | + | **.48** | < **.001** | + | .24 | .22 | - | .05 | .51 | + |
| DOC (µmol/l) | 0.0 | .88 | - | .03 | .444 | - | .051 | .26 | + | .22 | .14 | + |
| TDN (µmol/l) | .02 | .33 | - | .06 | .223 | - | .01 | .72 | + | .51 | **.01** | + |
| NH4+ (µmol/l) | .002 | .76 | - | .07 | .409 | + | .04 | .34 | + | .45 | **.03** | + |
| DON (µmol/l) | .04 | .14 | - | .37 | .072 | + | .002 | .82 | - | .62 | **.004** | + |
| TDP (µmol/l) | .001 | .86 | - | **.52** | < **.001** | + | .10 | .11 | + | .44 | **.03** | + |
| SRP (µmol/l) | .002 | .96 | - | **.46** | < **.001** | + | .11 | .051 | + | 0.0 | .20 | + |
| DOP (µmol/l) | .004 | .64 | - | .001 | .87 | + | .02 | .23 | + | .53 | **.01** | + |

Table 3.7. Linear regressions of Year 2 summer creek bank groundwater for marsh width (m) against salinity, DOC, nitrogen, and phosphorus; relationships examined for the individual creeks in (a) undeveloped and (b) developed watersheds; bold values indicate statistically significant ($p < 0.05$) relationships.

(a)

| | Crab Haul Creek | | | Village Creek | | | Guerin Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | $r^2$ | p | Slope | $r^2$ | p | Slope | $r^2$ | p | Slope |
| Salinity (ppt) | .51 | **.002** | + | .89 | .11 | + | .01 | .94 | + |
| DOC (µmol/l) | .20 | .08 | - | .01 | .91 | - | .34 | .42 | + |
| TDN (µmol/l) | .02 | .55 | - | .50 | .29 | + | .72 | .15 | + |
| NH4+ (µmol/l) | .10 | .21 | - | .58 | .24 | + | .80 | .10 | + |
| DON (µmol/l) | .06 | .36 | + | .25 | .51 | + | .17 | .59 | + |
| TDP (µmol/l) | .51 | **.003** | + | .91 | .09 | + | .07 | .73 | + |
| SRP (µmol/l) | .56 | **.001** | + | .67 | .18 | + | .08 | .72 | + |
| DOP (µmol/l) | 0 | .98 | - | | | | .47 | .53 | - |

(b)

| | Okatie Creek | | | Bulls Creek | | | Shem Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | $r^2$ | p | Slope | $r^2$ | p | Slope | $r^2$ | p | Slope |
| Salinity (ppt) | .001 | .90 | - | .03 | .76 | + | .03 | .78 | + |
| DOC (µmol/l) | .16 | .13 | - | .17 | .42 | + | .63 | .11 | + |
| TDN (µmol/l) | .38 | **.01** | - | .61 | .07 | + | .41 | .24 | + |
| NH4+ (µmol/l) | .26 | **.047** | - | .49 | .12 | + | .47 | .20 | + |
| DON (µmol/l) | .45 | **.004** | - | .71 | **.04** | + | .26 | .39 | + |
| TDP (µmol/l) | .37 | **.01** | - | .59 | .08 | + | .48 | .42 | + |
| SRP (µmol/l) | 0 | .97 | + | .34 | .52 | + | .40 | .25 | + |
| DOP (µmol/l) | .60 | **< .001** | - | .68 | **.04** | + | .01 | .90 | - |

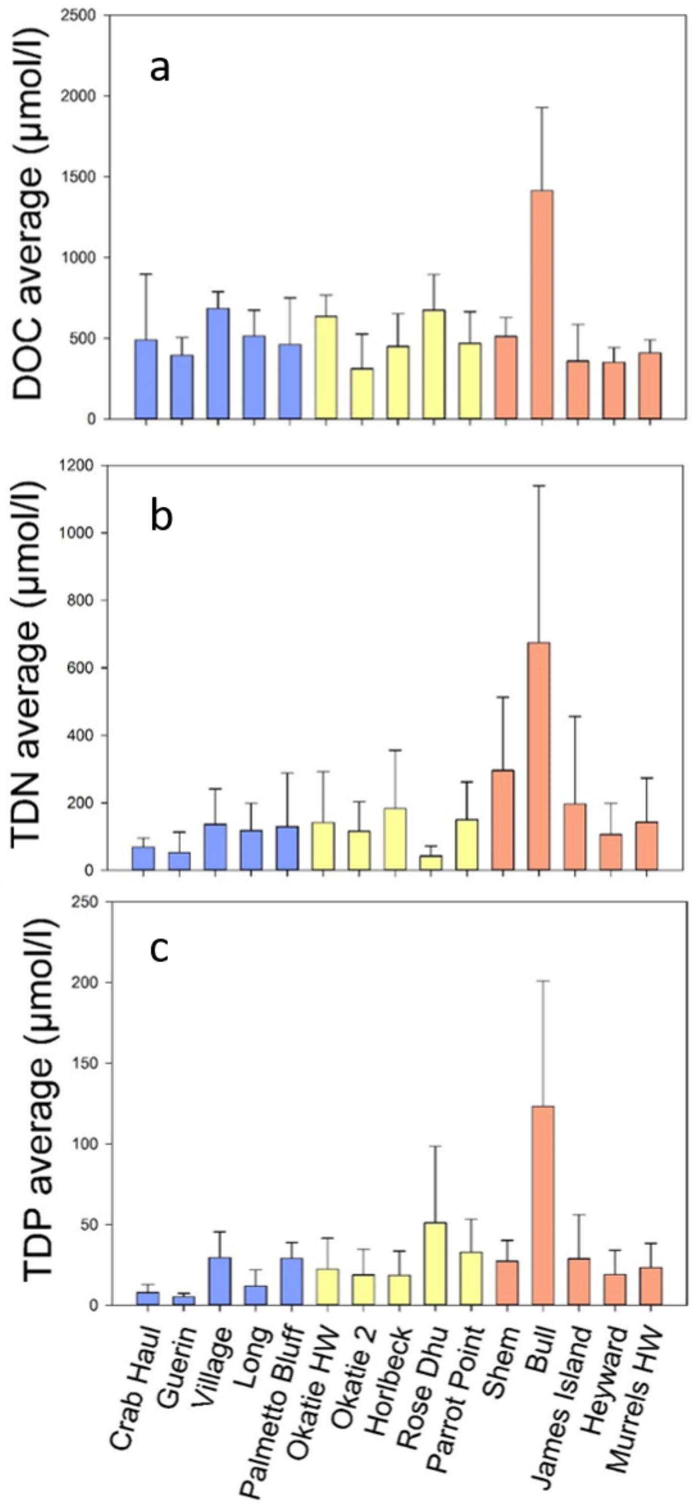


Figure 3.1 Year 1 summer creek bank groundwater average concentrations of (a) DOC, (b) TDN and (c) TDP with land-use class indicated by color (blue = forested, yellow = suburban, orange = urban); error bars are standard deviations.

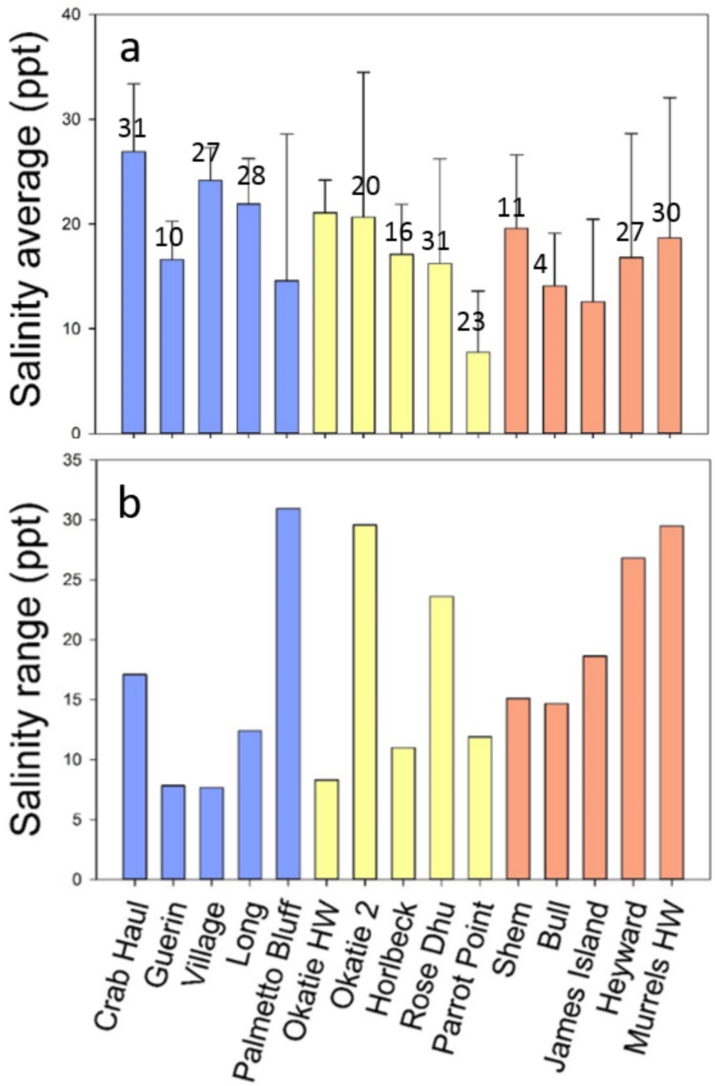


Figure 3.2 Year 1 summer creek bank groundwater (a) salinity averages and (b) salinity ranges for with land-use class indicated by color (blue = forested, yellow = suburban, orange = urban); error bars are standard deviations; floating numbers are surface water salinity values from Sanger et al. (2015).

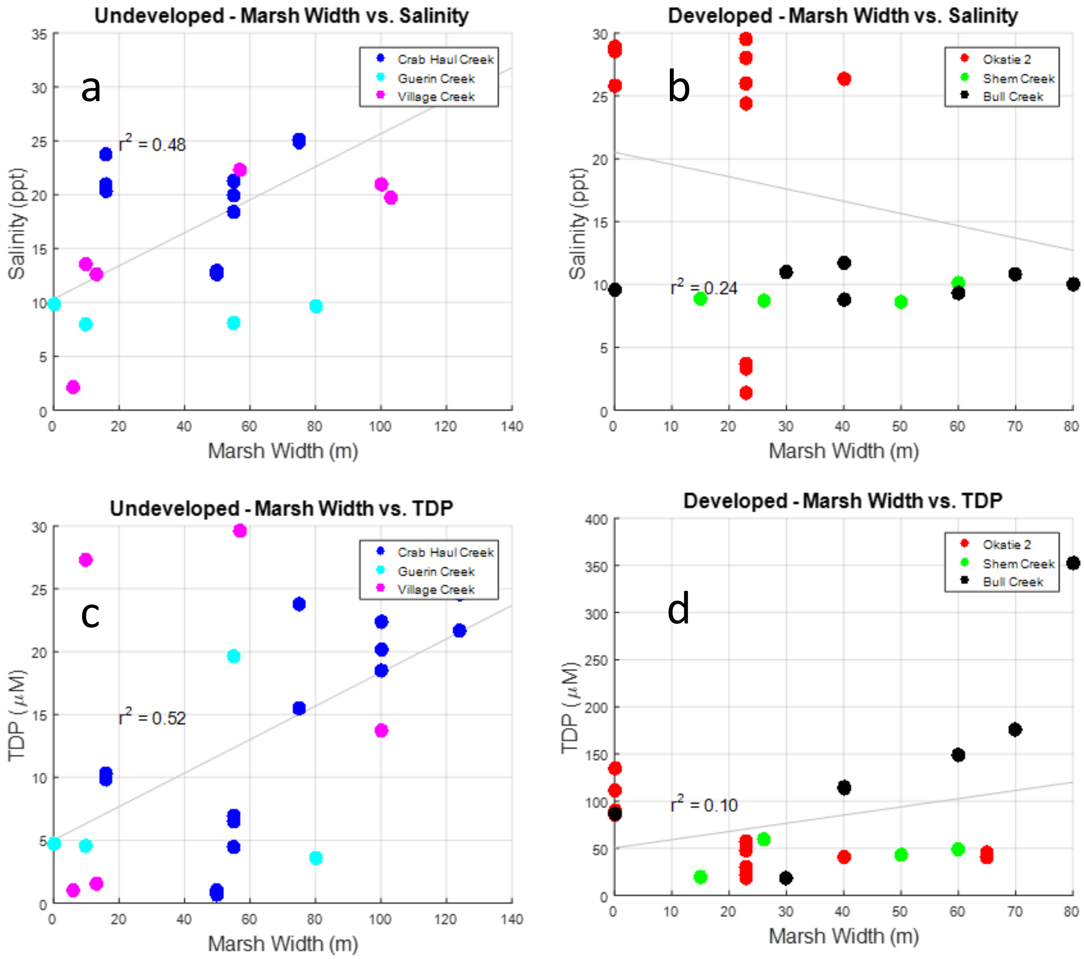


Figure 3.3. Linear regressions of constituents in Year 2 creekbank groundwater in (a, c) undeveloped and (b, d) developed watersheds against marsh width.

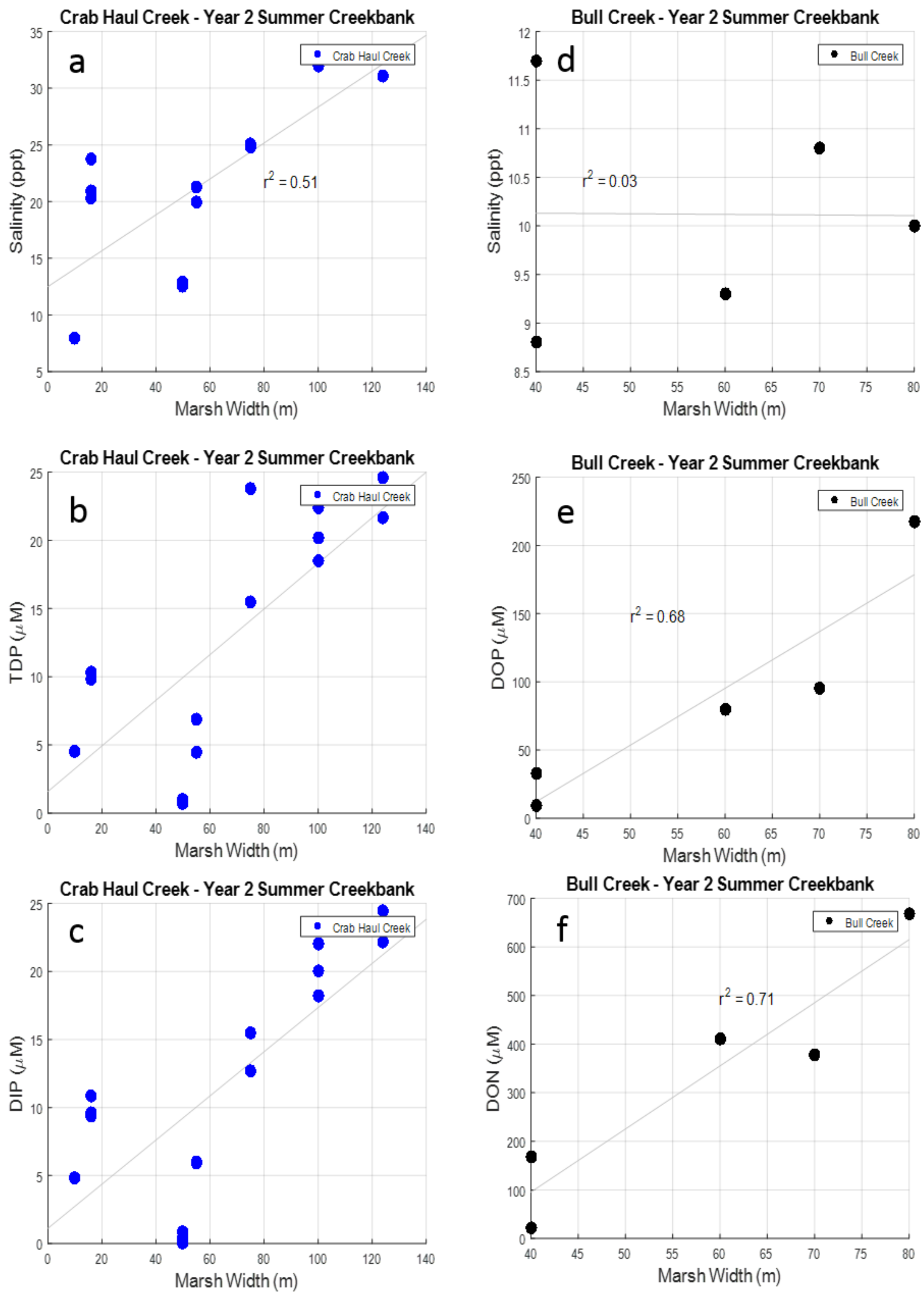


Figure 3.4. Linear regressions of creekbank groundwater at Crab Haul Creek for marsh width against (a) salinity, (b) TDP, (c) DIP and at Bulls Creek for marsh width again (d) salinity, (e) DOP, and (f) DON.

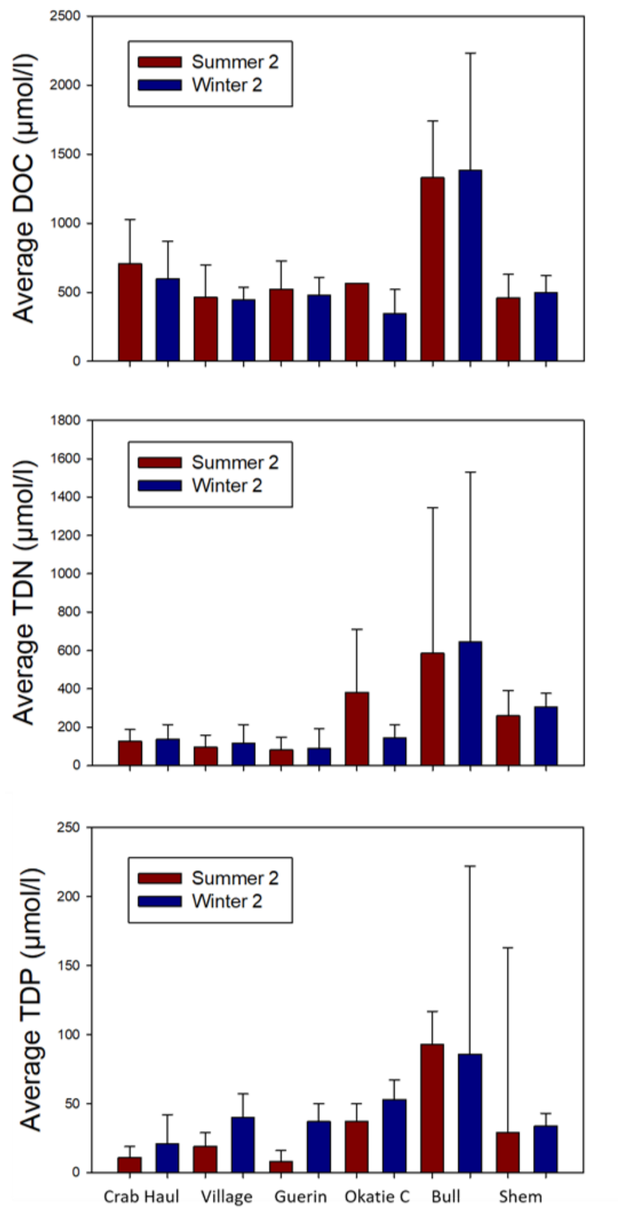


Figure 3.5 DOC, TDN and TDP concentrations for Year 2 summer and winter creek bank groundwater.

# CHAPTER 4

# DISCUSSION

## 4.1 STUDY LIMITATIONS

The limited number of creeks sampled during Year 2 did not allow for the removal of potential outliers. Bulls Creek, for example, had much higher concentrations of all water quality parameters than any of the other creeks sampled, and is likely an outlier site in that regard. Additionally, no soil samples were collected during either round of sampling. As discussed in the Introduction, the conceptual model for this project was largely informed by prior work performed at a limited number of tidal creeks located in undeveloped watersheds. Additional research supported the model of an approximately 1-2 m confining layer of mud overlying a sand layer (Carter et al. 2008, Harvey et al. 1987, Hemond and Fifield 1982, Weigart & Freeman 1991, Wilson et al. 2011, Wilson et al. 2015). However, visual observations made during this study suggest there is variability in the upper confining layer. Three creeks (Bulls Creek, Long Creek, and Guerin Creek) appeared to have a thicker upper layer with a potentially higher level of clay content. While not statistically significant, Sanger et al. (1999a, 1999b, 2015) also reported some variability in the upper 2 cm of sediment during sampling. Due to these findings, it is recommended that future works account for potential sediment variability and collect sediment samples when possible.

Results from Year 1 sampling demonstrate the potential variability in groundwater composition both within similar watershed types and within a single tidal creek basin. Additionally, it is important to note that samples collected during Year 1 and Year 2 represent a single snapshot in time. While controls were added to limit the level of variability (i.e. sampling during the same tidal window, not sampling following a major precipitation event when possible), a certain level of variability is inevitable when each site is visited a single time in a sampling season. Revisiting each creek multiple times over the course of a season and sampling at multiple areas along a creek bank would allow for a more robust data set in future projects.

## 4.2 MARSH WIDTH RELATIONSHIPS COMPLICATED BY CREEK VARIABIILITY

The conceptual model for this project was largely informed by previous research performed at Crab Haul Creek, located in a relatively pristine estuary in a forested watershed in Georgetown, SC. As discussed previously in the Methods, salt marshes at Crab Haul Creek are characterized by an approximately 1 m confining layer of mud overlying a sand layer (Wilson et al. 2011). One hypothesis of this study – that the width of salt marshes would correspond significantly with groundwater composition discharging along the creek bank – was true for certain variables at Crab Haul Creek. A possible explanation for this observed relationship is that a wider marsh allows for more tidally-driven mixing to occur in the sub-marsh aquifer zone between groundwater originating in the upland and surface water derived from the creek. The weakening of these relationships during the winter season, when mean sea levels are lower and creeks may therefore experience less tidal input and less mixing, appears to support this conceptual model.

Beyond Crab Haul Creek, the relationship between marsh width and groundwater composition varied. The maximum marsh width at Crab Haul Creek was larger than at the other creeks; it is possible that this extended marsh led to a stronger relationship. As discussed previously, sediment variability could also play an important role in the ability of marshes to store nutrients. The location of the creeks relative to the estuary could be a factor, as creeks located further inland may experience less tidally-driven groundwater mixing. Additionally, Year 1 demonstrated the potential variability when sampling within a single creek. As these sampling events were snapshots in time along a single reach of the creeks, it is possible that the relationships during Year 2 may have been more or less pronounced if a different section of each creek were sampled.

## 4.3 SEASONAL INFLUENCE ON GROUNDWATER COMPOSITION

Assessing groundwater composition in salt marsh tidal creeks is complicated by a variety of factors, including seasonal and tidal forces, spatiotemporal heterogeneity and anthropogenic impacts. Attempting to account and control for these factors improved results from Year 1 to Year 2 sampling, with clearer relationships emerging between groundwater composition and both marsh width and watershed development. Few significant seasonal differences were observed in overall concentrations of DOC and nutrients between Year 2 summer and winter. However, as previously discussed there were seasonal differences observed in the linear relationships between marsh width and groundwater composition, suggesting strong seasonal influences outside the scope of this study. While marsh width and tidally-driven mixing were observed during this study to be important controls within a seasonal sampling period, seasonal influence may be a stronger factor at an annual level.

# CHAPTER 5

# CONCLUSION

Assessing the impact of development and marsh width on groundwater composition in salt marsh tidal creeks is complicated by a variety of factors including seasonal and tidal forces, spatiotemporal heterogeneity and additional anthropogenic impacts. Results of this project show that watershed development can have significant impacts on overall groundwater composition, impacting the concentrations of DOC and nutrients in groundwater located both in the upland area and along the creek bank of salt marsh tidal creeks. In upland groundwater samples, nutrient concentrations were found to be significantly higher in developed watersheds, while DOC concentrations were found to be significantly higher in undeveloped watersheds, supporting previous work investigating the connection between watershed development and water quality (Hutchins et al. 2014, Sanger et al. 1999a, 1999b, 2015). While similar relationships were observed between creek bank groundwater and watershed development, concentrations measured in creek bank samples were often orders of magnitude higher than those in the upland area, suggesting that the tidal creeks and salt marshes act as an important source of certain forms of nutrients irrespective of groundwater input from the upland area.

The conceptual model for this project describes groundwater flow and sediment stratigraphy largely informed by prior work performed at tidal creeks located in undeveloped watersheds. Twice daily tides flood and drain the marsh, resulting in tidally driven groundwater-surface water mixing in the sub-marsh aquifer zone. Findings from this study, including the significant positive linear relationships observed between marsh width and salinity and nitrogen (TDN, $NH4^+$) concentrations at certain creeks, support the hypothesis that marsh width may influence groundwater composition. However, this project also highlights the potential for encountering unpredictable variability when sampling groundwater at a variety of field sites. For example, while previous studies of tidal creeks along the southeastern coastal US (Hutchins et al. 2014, Sanger et al. 1999a, 1999b, 2015) did not report sediment type as a significant factor in surface water quality, Sanger et al. (2015) did report some sediment variability between different creeks. This is supported by observational field notes from this study, and these sediment differences may have more influence in groundwater composition than in the surface water sampled in the previous works. Therefore, it is suggested that sediment samples be collected in future projects assessing groundwater quality in tidal creeks, as this will serve to clarify important biogeochemical processes. Additionally, while this project performed seasonal sampling, the numerous seasonally-affected environmental factors that could impact groundwater composition were outside of the scope of this work. To better address seasonal influence on groundwater composition in salt marsh tidal creeks, it would be beneficial to sample multiple times during a single season at each creek.

Overall, this work will serve to improve best management practices of tidal creeks along the southeastern coastal US. Understanding how watershed development impacts groundwater composition is crucial for managing ecosystems in tidal creeks, including phytoplankton composition and overall water quality. As coastal erosion grows and wetlands continue to shrink, it is critical to understand the relationship between marshes and groundwater composition.

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APPENDIX A

MARSH AND UPLAND WIDTH AND NUTRIENT RAW DATA

Table A.1 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Crab Haul Creek (CH) and Guerin Creek (GC), both in forested watersheds.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **CH** | | | | | | | | | | |
| 1 | 28.80 | 273.34 | 34.77 | 17.68 | 17.10 | 7.23 | 7.04 | 0.19 | 50 | 4000 |
| 2 | 26.60 | 1350.95 | 97.66 | 43.33 | 54.32 | 2.22 | 2.30 | -0.08 | 100 | 4000 |
| 3 | 29.40 | 348.99 | 72.13 | 38.75 | 33.38 | 14.82 | 15.01 | -0.19 | 250 | 4000 |
| 4 | 31.30 | 383.75 | 42.50 | 12.74 | 29.76 | 10.20 | 10.21 | -0.01 | 100 | 4000 |
| 5 | 31.20 | 236.89 | 101.51 | 56.99 | 44.52 | 11.00 | 11.38 | -0.38 | 150 | 1 |
| 6 | 25.50 | 442.45 | 138.79 | 82.13 | 56.66 | 5.18 | 5.13 | 0.05 | 360 | 4000 |
| **GC** | | | | | | | | | | |
| 1 | 14.17 | 362.77 | 35.21 | 22.87 | 12.34 | 6.36 | 5.99 | 0.37 | 1 | 70 |
| 2 | 15.81 | 463.22 | 141.91 | 109.23 | 32.68 | 6.10 | 6.19 | -0.09 | 1 | 350 |
| 4 | 14.54 | 258.93 | 14.25 | 2.62 | 11.63 | 2.25 | 1.43 | 0.82 | 1 | 0 |
| 5 | 21.42 | 550.53 | 40.73 | 21.77 | 18.95 | 3.04 | 1.13 | 1.91 | 50 | 350 |

Table A.2 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Palmetto Bluff (PB) and Long Creek (LC), both in forested watersheds.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **PB** | | | | | | | | | | |
| 1 | 26.27 | 447.96 | 117.67 | 86.95 | 30.72 | 26.05 | 27.41 | -1.36 | 22 | 457 |
| 2 | 0.23 | 105.03 | 15.49 | 11.19 | 4.30 | 38.64 | 39.89 | -1.24 | 11 | 1133 |
| 3 | 31.20 | 909.74 | 65.46 | 20.85 | 44.61 | 14.36 | 15.23 | -0.87 | 30 | 1187 |
| 4 | 13.50 | 446.69 | 405.64 | 318.88 | 86.77 | 37.11 | 26.22 | 10.89 | 22 | 882 |
| 5 | 1.83 | 8.09 | -0.75 | 0.45 | -1.20 | 0.33 | -0.01 | 0.34 | 17 | 882 |
| **LC** | | | | | | | | | | |
| 1 | 19.69 | 301.95 | 187.02 | 149.52 | 37.49 | 7.01 | 9.85 | -2.83 | 50 | 1100 |
| 2 | 25.21 | 429.10 | 52.24 | 27.57 | 24.67 | 7.95 | 8.48 | -0.53 | 20 | 1100 |
| 3 | 22.42 | 786.19 | 77.03 | 160.88 | -83.85 | 14.58 | 15.76 | -1.18 | 55 | 850 |
| 4 | 27.71 | 542.48 | 42.79 | 7.13 | 35.65 | 2.42 | 2.41 | 0.01 | 30 | 680 |
| 5 | 15.30 | 499.46 | 104.69 | 60.03 | 44.67 | 8.74 | 8.99 | -0.25 | 30 | 680 |
| 6 | 19.99 | 791.91 | 70.05 | 35.10 | 34.95 | 35.31 | 40.04 | -4.73 | 15 | 2100 |

Table A.3 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Village Creek (VC) and Rose Dhu (RD), in forested and suburban watersheds, respectively; D indicates where field duplicates were collected. . .

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **VC** | | | | | | | | | | |
| 1 | 19.99 | 791.91 | 70.05 | 35.10 | 34.95 | 35.31 | 40.04 | -4.92 | 0 | 2500 |
| 2 | 23.00 | 695.27 | 86.15 | 48.75 | 37.40 | 30.29 | 35.21 | -4.92 | 35 | 1600 |
| 3 | 27.68 | 662.42 | 34.00 | 0.90 | 33.10 | 2.37 | N/A | -4.92 | 39 | 1800 |
| 4 | 23.43 | 752.07 | 215.05 | 143.06 | 71.99 | 35.30 | 40.71 | -4.92 | 180 | 1600 |
| 6 | 26.77 | 523.41 | 278.46 | 205.56 | 72.90 | 44.58 | 61.87 | -4.92 | 67 | 2433 |
| **RD** | | | | | | | | | | |
| 1 | 24.60 | 797.42 | 45.21 | 12.05 | 33.16 | 83.82 | 90.10 | -6.28 | 36 | 1000 |
| 1D | 27.90 | 461.10 | 33.07 | 9.56 | 23.51 | 142.85 | 147.11 | -4.26 | 36 | 1000 |
| 2 | 27.50 | 686.37 | 120.42 | 71.18 | 49.24 | N/A | N/A | N/A | 30 | 1600 |
| 3 | 15.23 | 1097.71 | 34.11 | 5.78 | 28.33 | 47.35 | 97.01 | -49.66 | 32 | 1800 |
| 4 | 8.83 | 410.45 | 20.91 | 4.68 | 16.23 | 17.35 | 18.17 | -0.82 | 0 | 1600 |
| 5 | 8.83 | 427.19 | 21.83 | 4.47 | 17.37 | 14.10 | 14.53 | -0.43 | 190 | 2900 |
| 5D | 4.29 | 666.66 | 28.19 | 9.62 | 18.58 | 11.68 | 12.19 | -0.51 | 190 | 2900 |
| 6 | 4.29 | 716.89 | 30.03 | 10.02 | 20.01 | 13.16 | 11.94 | 1.22 | 0 | 2433 |
| 6D | 2.27 | 310.21 | 55.00 | 24.82 | 30.18 | 7.35 | 8.81 | -1.45 | 0 | 2433 |

Table A.4 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Parrot Point (PP), Horlbeck Creek (HC), and Okatie Creek HW (OHW), all in suburban watersheds.

| | Salinity (ppt) | DOC (μmol/l) | TDN (μmol/l) | $NH_4^+$ (μmol/l) | DON (μmol/l) | TDP (μmol/l) | SRP (μmol/l) | DOP (μmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **PP** | | | | | | | | | | |
| 1 | 3.43 | 622.16 | 241.12 | 99.67 | 141.45 | 51.92 | 42.48 | 9.44 | 27 | 1600 |
| 2 | 11.22 | 655.43 | 251.90 | 178.01 | 73.89 | 46.18 | 43.65 | 2.53 | 5 | 1600 |
| 3 | 14.17 | 291.14 | 52.31 | 26.99 | 25.33 | 26.53 | 27.59 | -1.06 | 0 | 1600 |
| 4 | 25.50 | 371.88 | 170.43 | 110.51 | 59.92 | 19.61 | 21.41 | -1.80 | 5 | 1600 |
| **HC** | | | | | | | | | | |
| 1 | 18.64 | 328.44 | 61.97 | 43.37 | 18.60 | 9.99 | 10.42 | -0.43 | 1 | 0 |
| 2 | 10.20 | 392.86 | 178.20 | 152.89 | 25.31 | 14.86 | 16.29 | -1.43 | 1 | 1 |
| 5 | 18.42 | 326.53 | 62.10 | 47.42 | 14.67 | 9.37 | 9.66 | -0.29 | 1 | 240 |
| 6 | 22.00 | 499.67 | 20.65 | 7.15 | 13.49 | 6.42 | 3.31 | 3.11 | 1 | 0 |
| **OHW** | | | | | | | | | | |
| 1 | 19.40 | 714.77 | 37.20 | 6.19 | 31.01 | 5.24 | 5.18 | 0.07 | 78 | 5600 |
| 2 | 17.62 | 643.99 | 68.09 | 35.67 | 32.42 | 28.93 | 30.53 | -1.60 | 38 | 4100 |
| 3 | 23.26 | 422.74 | 38.46 | 16.40 | 22.07 | 8.97 | 7.42 | 1.55 | 65 | 5600 |
| 4 | 18.90 | 762.45 | 375.84 | 299.81 | 76.03 | 41.93 | 46.01 | -4.08 | 40 | 4100 |
| 5 | 25.93 | 727.06 | 290.52 | 226.05 | 64.47 | 46.37 | 50.32 | -3.95 | 100 | 5600 |
| 6 | 3.12 | 319.75 | 40.13 | 27.56 | 12.56 | 2.52 | 0.67 | 1.85 | 188 | 5600 |

Table A.5 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Okatie Creek (OC), in a suburban watershed, and Murrels Headwaters (MHW) and James Island (JI) in urban watersheds.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **OC** | | | | | | | | | | |
| 3 | 29.64 | 468.94 | 164.98 | 126.72 | 38.26 | 28.61 | 34.02 | -5.41 | 0 | 1500 |
| 4 | 27.60 | 495.64 | 204.28 | 153.12 | 51.16 | 35.99 | 43.13 | -7.14 | 45 | 1500 |
| 5 | 25.30 | 246.00 | 87.86 | 71.18 | 16.68 | 8.45 | 4.32 | 4.14 | 65 | 1500 |
| 6 | 21.13 | 528.07 | 244.67 | 189.55 | 55.12 | 30.69 | 33.50 | -2.81 | 0 | 1500 |
| **MHW** | | | | | | | | | | |
| 1 | 30.00 | 264.23 | 75.44 | 50.96 | 24.48 | 18.83 | 19.28 | -0.45 | 0 | 7400 |
| 2 | 2.70 | 436.73 | 386.73 | 306.22 | 80.51 | 20.21 | 23.26 | -3.05 | 100 | 7400 |
| 3 | 25.20 | 420.20 | 170.49 | 105.57 | 64.92 | 15.29 | 16.66 | -1.38 | 65 | 1 |
| 4 | 28.20 | 382.90 | 55.41 | 32.99 | 22.42 | 33.48 | 33.09 | 0.40 | 0 | 300 |
| 5 | 0.51 | 505.18 | 31.47 | 13.28 | 18.20 | 47.60 | 49.44 | -1.85 | 130 | 7400 |
| 6 | 8.71 | 320.81 | 39.12 | 24.22 | 14.91 | 9.42 | 9.60 | -0.17 | 125 | 300 |
| **JI** | | | | | | | | | | |
| 1 | 19.75 | 667.51 | 648.82 | 384.40 | 264.42 | 74.95 | 48.08 | 26.87 | 40 | 1500 |
| 2 | 9.72 | 170.20 | 77.03 | 45.93 | 31.10 | 9.01 | 9.20 | -0.19 | 118 | 3400 |
| 3 | 21.70 | 504.12 | 185.73 | 132.51 | 53.22 | 31.01 | 34.82 | -3.81 | 0 | 2600 |
| 5 | 3.06 | 132.58 | 29.93 | 16.69 | 13.24 | 19.70 | 12.67 | 7.03 | 200 | 3200 |
| 6 | 24.60 | 805.47 | 42.71 | 7.84 | 34.86 | 78.84 | 82.34 | -3.50 | 14 | 2500 |

Table A.6 Marsh and upland widths and nutrient raw data from Year 1 summer creek bank groundwater for Heyward Cove (HWC), Shem Creek (SC), and Bulls Creek (BC), all in urban watersheds.

| | Salinity (ppt) | DOC (μmol/l) | TDN (μmol/l) | $NH_4^+$ (μmol/l) | DON (μmol/l) | TDP (μmol/l) | SRP (μmol/l) | DOP (μmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **HWC** | | | | | | | | | | |
| 1 | 26.90 | 414.69 | 201.22 | 93.13 | 108.09 | 42.87 | 47.90 | -5.03 | 30 | 340 |
| 2 | 22.00 | 464.49 | 199.26 | 98.88 | 100.38 | 30.08 | 35.89 | -5.81 | 27 | 1400 |
| 3 | 22.90 | 280.54 | 38.68 | 17.84 | 20.84 | 5.37 | 5.09 | 0.28 | 20 | 100 |
| 4 | 3.53 | 369.97 | 22.57 | 10.74 | 11.84 | 4.09 | 4.17 | -0.08 | 15 | 325 |
| 5 | 0.08 | 212.31 | 6.93 | 2.13 | 4.80 | 11.64 | 12.20 | -0.56 | 15 | 1400 |
| 6 | 14.21 | 575.75 | 478.60 | 307.59 | 171.01 | 28.39 | 28.98 | -0.59 | 0 | 1400 |
| **SC** | | | | | | | | | | |
| 1 | 10.08 | 655.86 | 70.60 | 21.37 | 49.24 | 7.62 | 8.02 | -0.40 | 21 | 2250 |
| 2 | 25.00 | 340.73 | 262.24 | 158.37 | 103.87 | 36.09 | 37.77 | -1.68 | 0 | 2200 |
| 3 | 25.20 | 495.64 | 558.17 | 327.46 | 230.71 | 41.15 | 38.76 | 2.39 | 85 | 1700 |
| 4 | 23.50 | 492.46 | 109.16 | 49.17 | 59.99 | 23.23 | 25.60 | -2.37 | 16 | 2000 |
| 5 | 21.20 | 750.16 | 429.27 | 333.63 | 95.64 | 40.63 | 37.37 | 3.26 | 62 | 2000 |
| **BC** | | | | | | | | | | |
| 1 | 10.19 | 986.24 | 63.81 | 10.52 | 53.29 | 14.46 | 18.44 | -3.98 | 0 | 1900 |
| 2 | 15.16 | 1688.54 | 484.29 | 189.11 | 295.18 | 186.08 | 197.20 | -11.12 | 0 | 1900 |
| 3 | 16.25 | 1479.16 | 770.00 | 413.01 | 357.00 | 116.24 | 123.15 | -6.91 | 64 | 1900 |
| 4 | 16.84 | 1800.43 | 1158.05 | 929.53 | 228.52 | 112.19 | 117.96 | -5.77 | 153 | 0 |
| 5 | 16.72 | 1533.42 | 591.16 | 458.36 | 132.80 | 171.78 | 181.46 | -9.69 | 111 | 145 |
| 6 | 16.83 | 1776.70 | 1203.34 | 30.93 | 1172.42 | 191.47 | 124.68 | 66.79 | 40 | 250 |
| 7 | 17.80 | 1728.81 | 1088.89 | 23.31 | 1065.58 | 191.65 | 136.76 | 54.89 | 0 | 0 |
| 8 | 1.83 | 398.58 | 44.82 | 28.11 | 16.72 | 28.96 | 30.03 | -1.07 | 0 | 0 |

Table A.7 Marsh and upland widths and nutrient raw data from Year 2 summer creek bank groundwater for Crab Haul Creek (CH), Village Creek (VC), and Guerin Creek (GC), all in undeveloped watersheds; note that triplicate samples were collected for each point at CH and the average values are reported.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **CH** | | | | | | | | | | |
| 1 | 19.85 | 649.57 | 134.93 | 107.29 | 27.64 | 5.95 | 6.09 | -0.14 | 55 | 4000 |
| 2 | 24.82 | 761.28 | 277.47 | 177.46 | 100.01 | 23.82 | 14.08 | -1.45 | 75 | 4000 |
| 3 | 12.77 | 1262.68 | 75.99 | 46.17 | 29.82 | 0.82 | 0.40 | 0.41 | 50 | 4000 |
| 4 | 21.67 | 652.46 | 168.16 | 142.08 | 26.08 | 10.14 | 9.95 | 0.19 | 16 | 0 |
| 5 | 32.13 | 336.89 | 70.29 | 43.54 | 26.75 | 20.37 | 20.08 | 0.29 | 100 | 4000 |
| 6 | 31.15 | 556.73 | 139.16 | 95.94 | 43.22 | 23.28 | 23.32 | 7.74 | 124 | 4000 |
| **VC** | | | | | | | | | | |
| 1 | 13.52 | 466.02 | 148.42 | 126.76 | 21.67 | 27.33 | 27.17 | 0.16 | 10 | 3000 |
| 2 | 22.26 | 539.37 | 71.48 | 42.16 | 29.32 | 29.56 | 21.33 | 8.23 | 57 | 3000 |
| 3 | 19.73 | 468.30 | 195.64 | 144.58 | 51.06 | 26.77 | 31.71 | -4.94 | 103 | 3000 |
| 4 | 20.93 | 348.04 | 67.70 | 52.13 | 15.58 | 13.73 | 15.57 | -1.84 | 100 | 3000 |
| 5 | 13 | 837.11 | 63.03 | 32.40 | 30.63 | 1.55 | 9.65 | -8.10 | 13 | 3000 |
| 6 | 2 | 126.05 | 22.57 | 17.95 | 4.62 | 1.05 | 6.88 | -5.83 | 6 | 3000 |
| **GC** | | | | | | | | | | |
| 1 | 8.00 | 396.60 | 25.69 | 14.87 | 10.82 | 4.51 | 4.79 | -0.28 | 10 | 2700 |
| 2 | 8.10 | 811.70 | 158.23 | 125.60 | 32.63 | 19.67 | 19.74 | -0.07 | 55 | 2700 |
| 3 | 8.20 | 577.80 | 191.80 | 165.86 | 25.94 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| 4 | 9.60 | 504.45 | 113.64 | 100.19 | 13.45 | 3.57 | 3.40 | 0.17 | 80 | 2700 |
| 5 | 9.40 | 567.89 | 53.84 | 35.75 | 18.08 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| 6 | 9.80 | 373.87 | 23.02 | 10.88 | 12.14 | 4.70 | 4.04 | 0.66 | 0 | 2700 |

Table A.8 Marsh and upland widths and nutrient raw data from Year 2 summer creek bank groundwater for Okatie Creek (OC), Bulls Creek (BC), and Shem Creek (SC), all in developed watersheds.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **OC** | | | | | | | | | | |
| 2 | 27.00 | 599.65 | 201.42 | 113.22 | 88.21 | 47.05 | 27.91 | 19.13 | 23 | 1500 |
| 3 | 26.23 | 533.59 | 254.54 | 173.41 | 81.13 | 43.35 | 46.21 | -2.86 | 65 | 1500 |
| 4 | 26.37 | 487.72 | 221.33 | 156.34 | 64.99 | 40.48 | 44.84 | -4.36 | 40 | 1500 |
| 5 | 2.77 | 64.11 | 54.44 | 49.56 | 4.88 | 22.16 | 19.99 | 2.17 | 23 | 1500 |
| 6 | 28.14 | 874.22 | 832.46 | 357.80 | 474.66 | 102.18 | 47.82 | 54.36 | 0 | 1500 |
| **BC** | | | | | | | | | | |
| 1 | 9.60 | 1352.05 | 113.58 | 55.91 | 57.67 | 86.45 | 85.67 | 0.78 | 0 | 2000 |
| 2 | 8.80 | 1294.71 | 400.05 | 232.02 | 168.03 | 115.00 | 82.35 | 32.65 | 40 | 2000 |
| 3 | 9.30 | 1237.89 | 645.26 | 234.21 | 411.05 | 149.08 | 69.25 | 79.83 | 60 | 2000 |
| 4 | 10.00 | 2055.59 | 1649.34 | 981.76 | 667.58 | 352.71 | 135.27 | 217.44 | 80 | 2000 |
| 5 | 10.80 | 1251.32 | 652.95 | 275.26 | 377.69 | 175.51 | 80.13 | 95.38 | 70 | 2000 |
| 6 | 11.70 | 784.36 | 54.99 | 33.10 | 21.89 | 113.30 | 103.75 | 9.56 | 40 | 2000 |
| **SC** | | | | | | | | | | |
| 1 | 8.90 | 220.56 | 104.92 | 86.35 | 18.57 | 19.06 | 8.80 | 10.26 | 15 | 2000 |
| 2 | 8.70 | 561.48 | 374.51 | 79.39 | 295.12 | 59.20 | 42.55 | 16.65 | 26 | 2000 |
| 3 | 8.60 | 533.79 | 334.34 | 161.12 | 173.23 | 43.37 | 32.46 | 10.90 | 50 | 2000 |
| 4 | 10.10 | 632.77 | 354.59 | 111.27 | 243.32 | 48.95 | 40.44 | 8.51 | 60 | 2000 |
| 5 | 11.00 | 348.04 | 125.87 | 86.11 | 39.76 | 18.22 | 23.04 | -4.82 | 30 | 2000 |

Table A.9 Marsh and upland widths and nutrient raw data from Year 2 winter creek bank groundwater for Crab Haul Creek (CH) located in an undeveloped watershed.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **CH** | | | | | | | | | | |
| 1 | 21.73 | 711.14 | 160.26 | 113.56 | 46.70 | 5.02 | N/A | N/A | 97 | 4000 |
| 2 | 32.42 | 377.23 | 55.75 | 39.86 | 15.89 | 7.05 | N/A | N/A | 61 | 4000 |
| 3 | 24.52 | 784.61 | 224.13 | 126.06 | 98.07 | 17.56 | N/A | N/A | 134 | 4000 |
| 4 | 9.51 | 1164.90 | 57.24 | 22.63 | 34.61 | 73.00 | N/A | N/A | 147 | 4000 |
| 5 | 32.61 | 209.95 | 24.56 | 12.82 | 11.74 | 4.06 | N/A | N/A | 134 | 4000 |
| 6 | 30.85 | 568.43 | 145.83 | 95.76 | 50.07 | 32.31 | N/A | N/A | 147 | 4000 |
| 7 | 31.08 | 563.98 | 124.37 | 74.34 | 50.04 | 18.52 | N/A | N/A | 72 | 4000 |
| 8 | 30.86 | 476.32 | 175.30 | 116.44 | 58.87 | 12.30 | N/A | N/A | 70 | 4000 |
| 9 | 31.43 | 531.80 | 252.56 | 149.68 | 102.87 | 19.85 | N/A | N/A | 97 | 4000 |

Table A.10 Marsh and upland widths and nutrient raw data from Year 2 winter creek bank groundwater for Guerin Creek (GC) and Village Creek (VC), both located in undeveloped watersheds.

| | Salinity (ppt) | DOC (μmol/l) | TDN (μmol/l) | $NH_4^+$ (μmol/l) | DON (μmol/l) | TDP (μmol/l) | SRP (μmol/l) | DOP (μmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **VC** | | | | | | | | | | |
| 1 | 6.57 | 410.68 | 126.37 | 113.99 | 12.38 | 24.46 | 11.08 | 13.37 | 45 | 3000 |
| 2 | 22.18 | 483.31 | 72.62 | 42.91 | 29.71 | 45.79 | 27.53 | 18.26 | 70 | 3000 |
| 3 | 19.88 | 553.82 | 306.86 | 222.96 | 83.90 | 63.63 | 56.40 | 7.23 | 131 | 3000 |
| 4 | 20.69 | 383.15 | 88.32 | 58.79 | 29.53 | 39.99 | 17.53 | 22.46 | 115 | 3000 |
| 5 | 18.12 | 521.42 | 64.21 | 46.53 | 17.68 | 50.97 | 27.90 | 23.07 | 5 | 3000 |
| 6 | 0.43 | 312.64 | 30.46 | 22.73 | 7.73 | 17.02 | 10.68 | 6.34 | 0 | 3000 |
| **GC** | | | | | | | | | | |
| 1 | 19.36 | 385.91 | 17.07 | 5.51 | 11.56 | 38.05 | 6.45 | 31.60 | 18 | 2700 |
| 2 | 16.42 | 465.10 | 43.30 | 25.62 | 17.67 | 59.02 | 7.54 | 51.48 | 66 | 2700 |
| 3 | 15.64 | 696.32 | 270.86 | 79.94 | 190.92 | 34.86 | 4.01 | 30.85 | 78 | 2700 |
| 4 | 12.01 | 468.06 | 146.16 | 22.66 | 123.50 | 23.00 | 2.51 | 20.49 | 90 | 2700 |
| 5 | 20.56 | 524.17 | 43.37 | 253.94 | -210.57 | 42.26 | 6.42 | 35.84 | 52 | 2700 |
| 6 | 16.86 | 310.74 | 25.97 | 17.41 | 8.56 | 27.44 | N/A | N/A | 12 | 2700 |

Table A.11 Marsh and upland widths and nutrient raw data from Year 2 winter creek bank groundwater for Okatie Creek (OC), Bulls Creek (BC) and Shem Creek (SC), all located in developed watersheds.

| | Salinity (ppt) | DOC (µmol/l) | TDN (µmol/l) | $NH_4^+$ (µmol/l) | DON (µmol/l) | TDP (µmol/l) | SRP (µmol/l) | DOP (µmol/l) | Marsh Width (m) | Upland Width (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **OC** | | | | | | | | | | |
| 1 | 27.72 | 507.87 | 159.16 | 114.37 | 44.79 | 58.31 | 33.35 | 24.97 | 48 | 1500 |
| 2 | 26.54 | 464.04 | 158.60 | 119.80 | 38.81 | 57.47 | 36.09 | 21.38 | 42 | 1500 |
| 3 | 24.78 | 393.95 | 136.21 | 118.86 | 17.35 | 52.79 | 24.22 | 28.57 | 44 | 1500 |
| 4 | 25.09 | 428.89 | 249.24 | 114.55 | 134.69 | 72.50 | 37.76 | 34.74 | 30 | 1500 |
| 5 | 17.17 | 229.01 | 128.63 | 43.21 | 85.43 | 44.92 | 16.47 | 28.45 | 13 | 1500 |
| 6 | 1.46 | 52.88 | 38.78 | 191.55 | -152.76 | 29.79 | 23.11 | 6.67 | 8 | 1500 |
| **BC** | | | | | | | | | | |
| 1 | 17.37 | 982.24 | 154.03 | 121.19 | 32.84 | 9.35 | N/A | N/A | 5 | 2000 |
| 2 | 17.00 | 1201.39 | 313.56 | 119.40 | 194.16 | 17.26 | N/A | N/A | 71 | 2000 |
| 3 | 11.64 | 2959.89 | 2420.28 | 721.28 | 1699.00 | 352.98 | N/A | N/A | 91 | 2000 |
| 4 | 13.92 | 1192.39 | 449.32 | 204.32 | 245.00 | 17.20 | N/A | N/A | 91 | 2000 |
| 5 | 18.01 | 1522.70 | 482.36 | 229.47 | 252.89 | 105.44 | N/A | N/A | 76 | 2000 |
| 6 | 6.62 | 446.22 | 56.22 | 29.12 | 27.10 | 13.81 | N/A | N/A | 76 | 2000 |
| **SC** | | | | | | | | | | |
| 1 | 11.08 | 391.20 | 300.61 | 193.93 | 106.68 | 26.01 | N/A | N/A | 31 | 2700 |
| 2 | 11.44 | 385.06 | 304.15 | 237.36 | 66.79 | 27.17 | N/A | N/A | 33 | 2000 |
| 3 | 24.43 | 468.70 | 237.74 | 158.18 | 79.56 | 31.37 | N/A | N/A | 62 | 2000 |
| 4 | 24.60 | 452.82 | 228.72 | 169.85 | 58.88 | 30.69 | N/A | N/A | 62 | 2000 |
| 5 | 26.21 | 597.01 | 367.30 | 160.87 | 206.43 | 35.67 | N/A | N/A | 65 | 2000 |
| 6 | 27.37 | 692.93 | 402.14 | 53.02 | 349.12 | 50.30 | N/A | N/A | 65 | 2000 |

# APPENDIX B

# STATISTICAL DATA

Table B.1 Linear regression results of Year 1 summer creek bank samples for marsh width against salinity, DOC, nitrogen, and phosphorus; relationships examined by watershed type; bold values indicate statistically significant ($p < 0.05$) relationships.

| Parameter | All Creeks | | | Forested | | | Suburban | | | Urban | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $r^2$ | p | Slope | $r^2$ | p | Slope | $r^2$ | p | Slope | $r^2$ | P | Slope |
| Salinity (ppt) | 0 | .94 | - | .17 | **.04** | + | .06 | .21 | - | .13 | .05 | - |
| DOC (µmol/l) | 0 | .98 | + | 0 | .94 | + | .001 | .85 | + | 0 | .98 | + |
| TDN (µmol/l) | .001 | .76 | + | .03 | .42 | + | .04 | .34 | - | .02 | .52 | + |
| $NH_4^+$ (µmol/l) | .02 | .24 | + | .01 | .66 | + | .03 | .38 | - | .13 | **.046** | + |
| DON (µmol/l) | .003 | .61 | - | .07 | .19 | + | .03 | .36 | - | .01 | .56 | - |
| TDP (µmol/l) | .004 | .55 | - | .01 | .68 | - | .02 | .5 | - | 0 | .98 | + |
| SRP (µmol/l) | .004 | .57 | - | .01 | .72 | - | .02 | .49 | - | .001 | .86 | + |
| DOP (µmol/l) | .001 | .82 | - | 0 | .92 | - | .004 | .76 | + | .01 | .64 | - |

Table B.2 Mean (standard deviation) values for Year 2 summer and winter upland groundwater samples; abbreviations are for all (A), undeveloped (U) and developed (D) watersheds, and Year 2 Summer (S2) and Winter (W2).

| Parameter | Year 2 All Seasons | | | Year 2 Summer | | | Year 2 Winter | | |
|---|---|---|---|---|---|---|---|---|---|
| | All | U | D | S2 All | S2 U | S2 D | W2 A | W2 U | W2 D |
| DOC (µmol/l) | 759 (658) | 933 (637) | 549 (632) | 936 (716) | 1215 (760) | 638 (545) | 560 (532) | 651 (305) | 436 (740) |
| TDN (µmol/l) | 75 (81) | 62 (22) | 89 (117) | 89 (100) | 57 (23) | 122 (136) | 59 (50) | 68 (21) | 46 (73) |
| $NH_4^+$ (µmol/l) | 50 (72) | 31 (22) | 71 (101) | 59 (92) | 20 (11) | 101 (120) | 39 (40) | 43 (25) | 34 (55) |
| DON (µmol/l) | 25 (25) | 31 (18) | 17 (30) | 29 (22) | 37 (22) | 21 (19) | 20 (27) | 25 (11) | 13 (40) |
| TDP (µmol/l) | 18 (66) | 7 (7) | 32 (96) | 27 (91) | 6 (8) | 52 (126) | 7 (6) | 8 (7) | 6 (5) |
| SRP (µmol/l) | N/A | N/A | N/A | 5 (6) | 5 (8) | 4 (4) | N/A | N/A | N/A |
| DOP (µmol/l) | N/A | N/A | N/A | 24 (91) | 0 (1) | 48 )127) | N/A | N/A | N/A |

Table B.3 Year 2 winter creek bank groundwater for individual creeks located in (a) undeveloped and (b) developed watersheds.

(a)

| | Crab Haul Creek | | | Village Creek | | | Guerin Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) |
| Salinity (ppt) | 9.51 | 32.61 | 26.8 (8.03) | 0.43 | 22.18 | 14.6 (8.95) | 12.01 | 20.56 | 16.8 (3.00) |
| DOC (µmol/l) | 210 | 1164 | 599 (271) | 313 | 554 | 444 (91) | 310.74 | 696.32 | 476(132) |
| TDN (µmol/l) | 25 | 253 | 136 (78) | 31 | 307 | 115 (99) | 17.07 | 270.86 | 91 (100) |
| $NH_4^+$ (µmol/l) | 13 | 150 | 83 (49) | 23 | 223 | 85 (74) | 12.82 | 149.68 | 68 (95) |
| DON (µmol/l) | 12 | 103 | 52 (32) | 8 | 84 | 30 (28) | 8.56 | 66.22 | 24 (21) |
| TDP (µmol/l) | 4 | 73 | 21 (21) | 17 | 64 | 40 (17) | 23 | 59 | 37 (13) |
| SRP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| DOP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

(b)

| | Okatie Creek | | | Bulls Creek | | | Shem Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) | Min | Max | Mean (Std. Dev) |
| Salinity (ppt) | 1.46 | 27.72 | 20.5 (10.0) | 6.62 | 18.01 | 14.1 (4.39) | 11.08 | 27.37 | 20.9 (7.51) |
| DOC (µmol/l) | 53 | 508 | 346 (173) | 446 | 2960 | 1384 (850) | 385 | 693 | 498 (122) |
| TDN (µmol/l) | 39 | 249 | 145 (68) | 56 | 2420 | 646 (885) | 229 | 402 | 307 (69) |
| $NH_4^+$ (µmol/l) | 43 | 192 | 117 (47) | 29 | 721 | 237 (247) | 53 | 237 | 162 (61) |
| DON (µmol/l) | 0 | 58 | 29 (22) | 27 | 1699 | 409 (640) | 59 | 349 | 145 (114) |
| TDP (µmol/l) | 30 | 73 | 53 (14) | 9 | 353 | 86 (136) | 26 | 50 | 34 (9) |
| SRP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| DOP (µmol/l) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table B.4. Linear regression of Year 2 winter creek bank samples for marsh width (m) against salinity, DOC, nitrogen, and phosphorus; relationships examined for the individual creeks in (a) undeveloped and (b) developed watersheds; bold values indicate statistically significant ($p < 0.05$) relationships.

(a)

| | Crab Haul Creek | | | Village Creek | | | Guerin Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | $r^2$ | p | Slope | $r^2$ | P | Slope | $r^2$ | p | Slope |
| Salinity (ppt) | .22 | **.21** | - | .41 | .17 | + | .41 | .17 | + |
| DOC (µmol/l) | .18 | .26 | + | .13 | .49 | + | .51 | .11 | + |
| TDN (µmol/l) | .01 | .80 | - | .51 | .11 | + | .50 | .12 | + |
| $NH_4^+$ (µmol/l) | .04 | .63 | - | .43 | .16 | + | .02 | .79 | + |
| DON (µmol/l) | .002 | .91 | + | .64 | .057 | + | .17 | .41 | + |
| TDP (µmol/l) | .29 | .13 | + | .34 | .23 | + | .001 | .95 | + |

(b)

| | Okatie Creek | | | Bulls Creek | | | Shem Creek | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | $r^2$ | P | Slope | $r^2$ | P | Slope | $r^2$ | P | Slope |
| Salinity (ppt) | .76 | **.02** | + | .17 | .42 | - | .994 | **< 0.001** | + |
| DOC (µmol/l) | .85 | **.009** | + | .14 | .47 | + | .56 | .09 | + |
| TDN (µmol/l) | .26 | .30 | + | .18 | .40 | + | .02 | .07 | + |
| $NH_4^+$ (µmol/l) | .01 | .86 | + | .15 | .44 | + | .49 | .12 | + |
| DON (µmol/l) | .16 | .44 | + | .19 | .39 | + | .21 | .36 | + |
| TDP (µmol/l) | .43 | .16 | + | .16 | .43 | - | .43 | .16 | + |

APPENDIX C

FIELD SITES AND CREEK BANK SAMPLING LOCATIONS

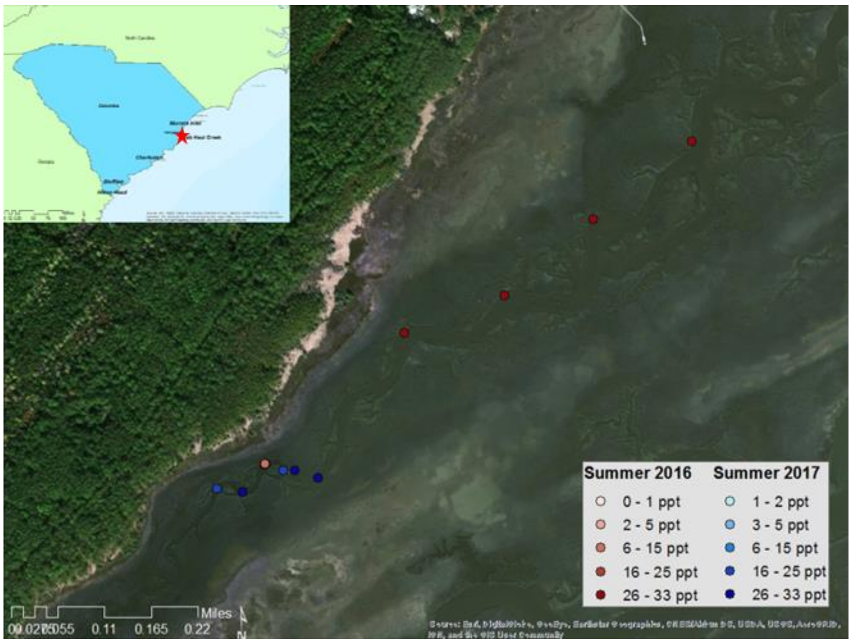


Figure C.1 Locations of sampling points at Crab Haul Creek located in an undeveloped (forested) watershed in Georgetown, SC; salinity values for Year 1 summer (red) and Year 2 summer (blue) are shown for each point.

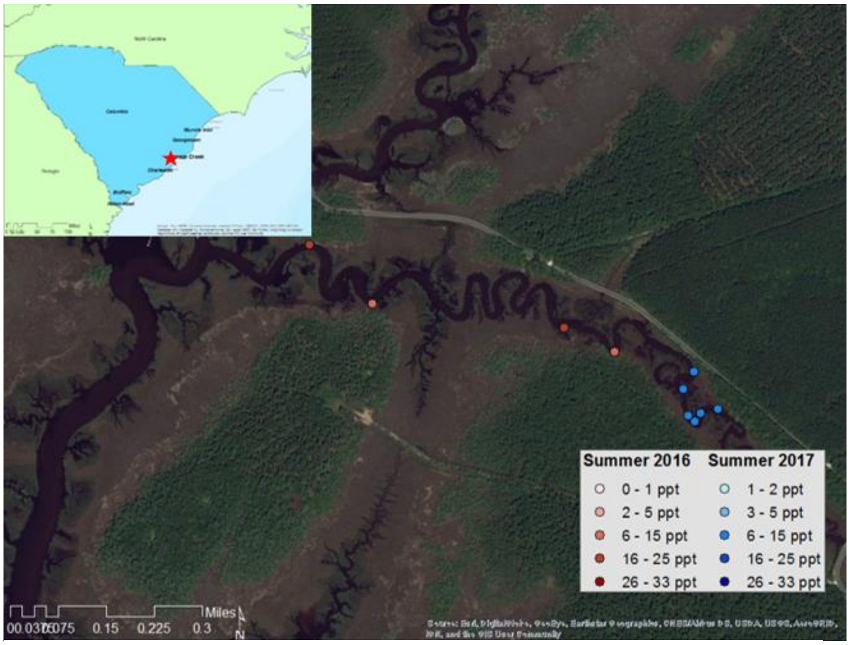


Figure C.2 Locations of sampling points at Guerin Creek located in an undeveloped (forested) watershed in Charleston, SC; salinity values for Year 1 summer (red) and Year 2 summer (blue) are shown for each point.

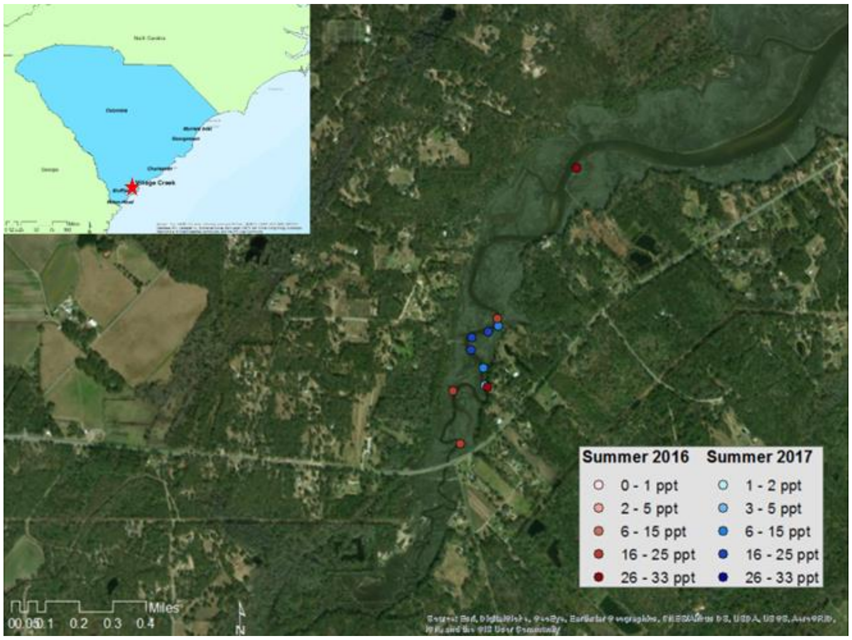


Figure C.3 Locations of sampling points at Village Creek located in an undeveloped (forested) watershed in Mt Pleasant, SC; salinity values for Year 1 summer (red) and Year 2 summer (blue) are shown for each point.

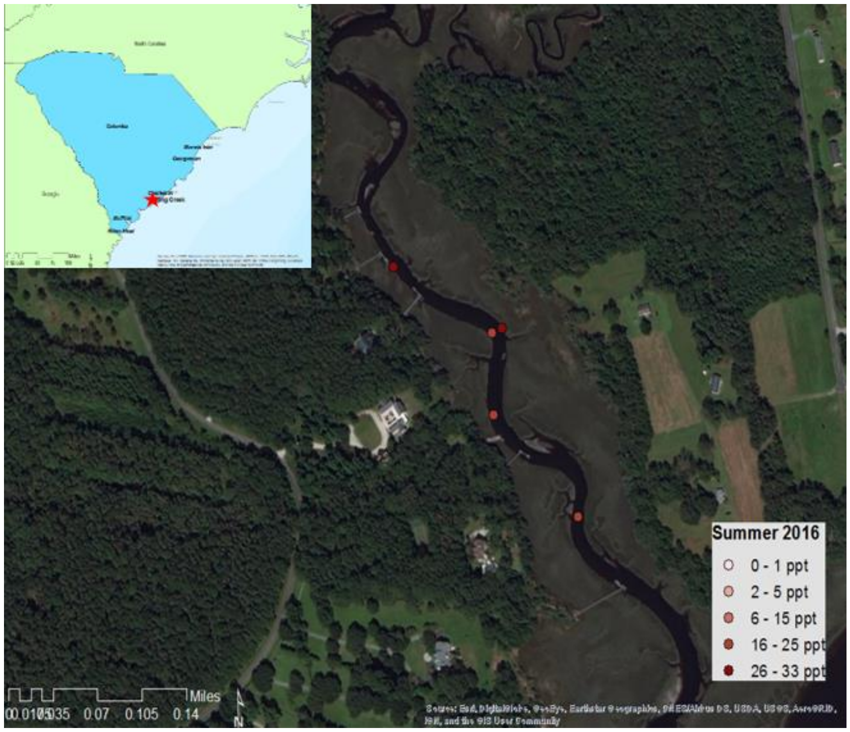


Figure C.4 Locations of sampling points at Long Creek located in an undeveloped (forested) watershed in Wadmalaw Island, SC; salinity values for Year 1 summer (red) and Year 2 summer

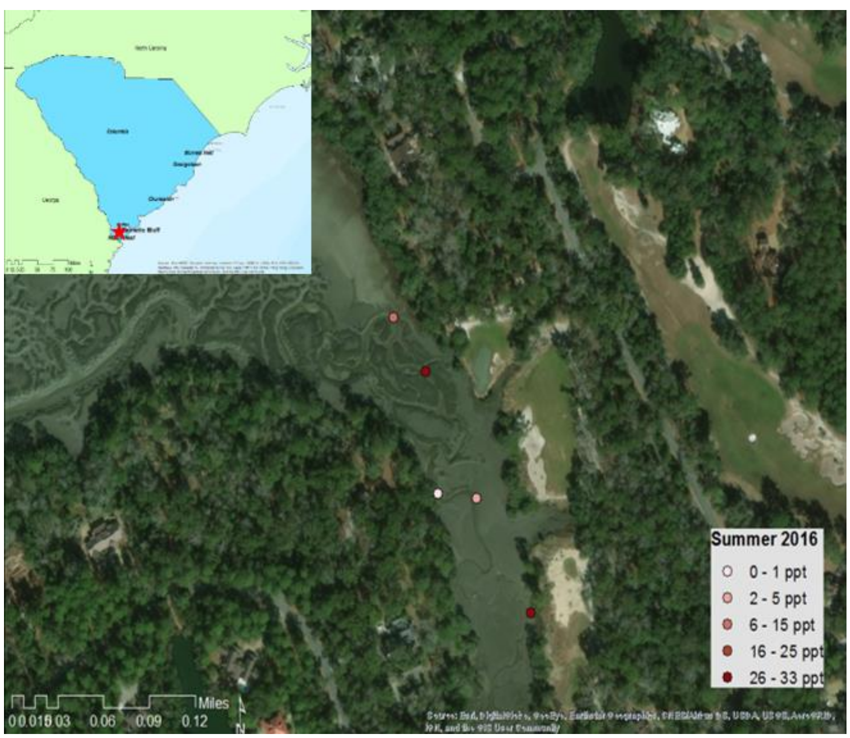


Figure C.5 Locations of sampling points at Palmetto Bluff located in an undeveloped (forested) watershed in Bluffton, SC; salinity values for Year 1 summer (red) are shown for each point.

Figure C.6 Locations of sampling points at Okatie Creek HW located in a developed (suburban) watershed in Bluffton, SC; salinity values for Year 1 summer (red) are shown for each point.

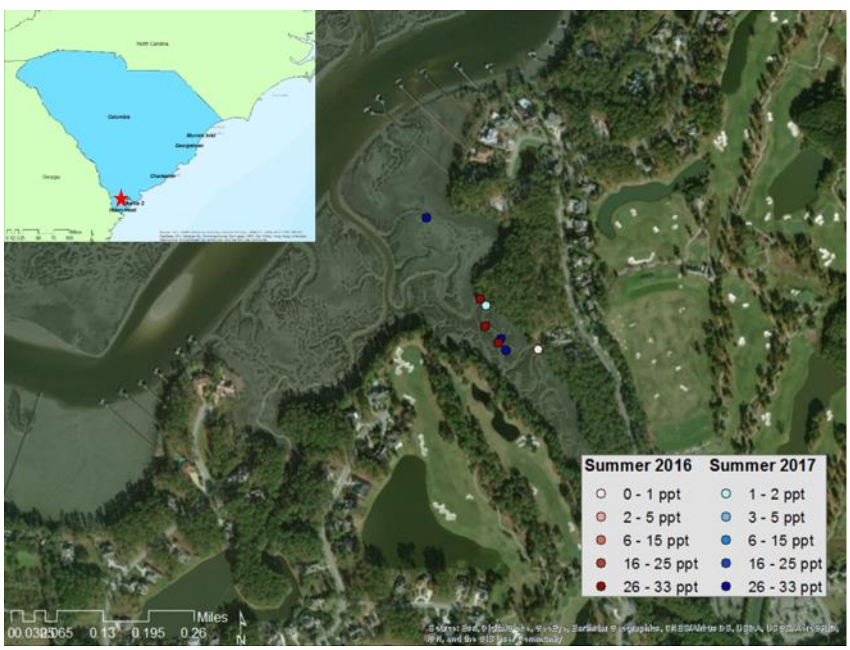

Figure C.7 Locations of sampling points at Okatie Creek located in a developed (suburban) watershed in Bluffton, SC; salinity values for Year 1 summer (red) and Year 2 (blue) are shown for

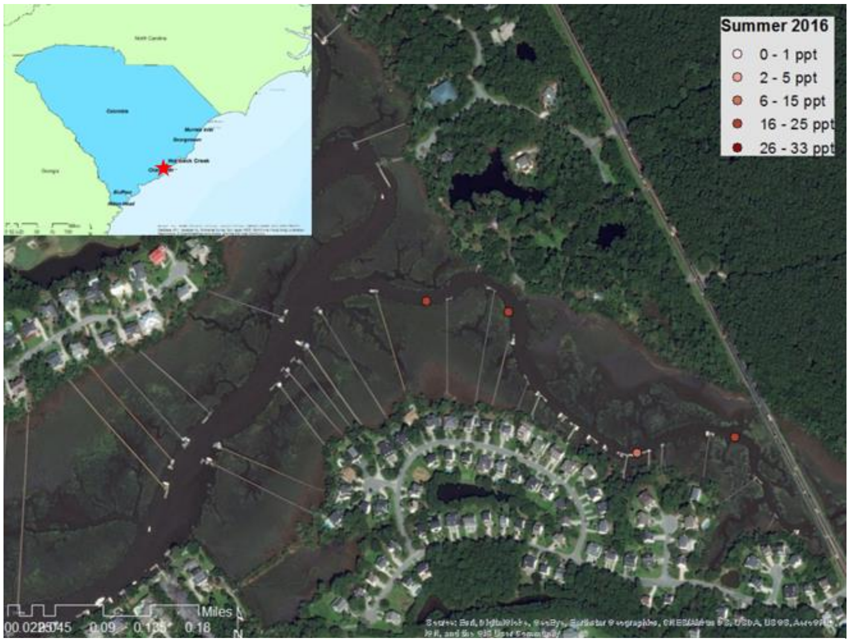

Figure C.8 Locations of sampling points at Horlbeck located in a developed (suburban) watershed in Mt Pleasant, SC; salinity values for Year 1 summer (red) are shown for each point.

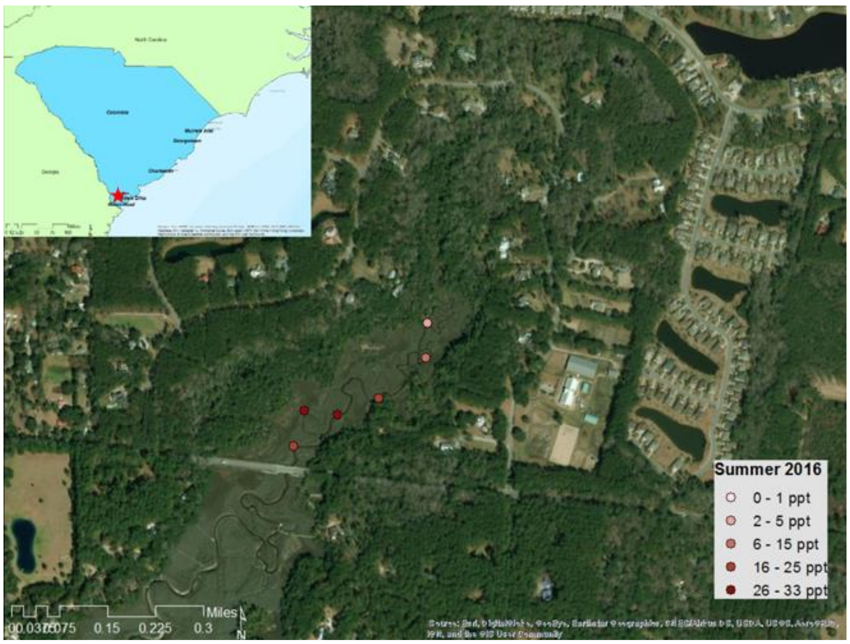

Figure C.9 Locations of sampling points at Rose Dhu located in a developed (suburban) watershed in Bluffton, SC; salinity values for Year 1 summer (red) are shown for each point.


Figure C.10 Locations of sampling points at Parrot Point located in a developed (suburban) watershed in Charleston, SC; salinity values for Year 1 summer (red) are shown for each point.

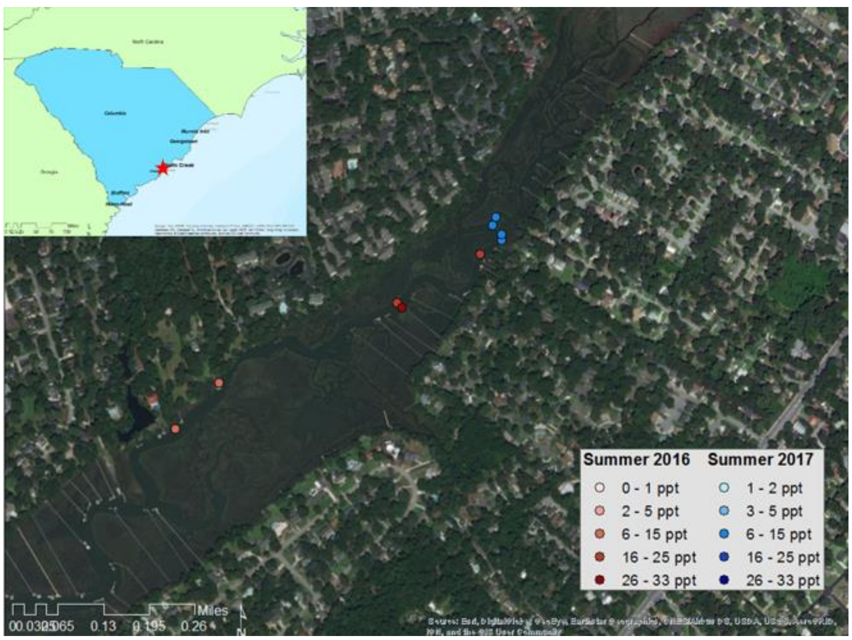


Figure C.11 Locations of sampling points at Shem Creek located in a developed (urban) watershed in Charleston, SC; salinity values for Year 1 summer (red) and Year 2 (blue) are shown for each point.

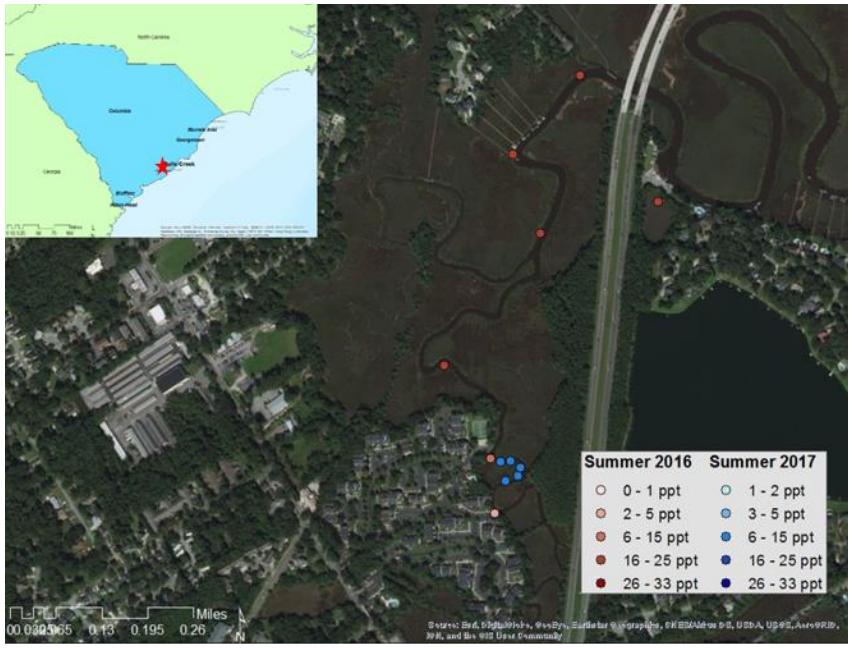


Figure C.12 Locations of sampling points at Bulls Creek located in a developed (urban) watershed in Charleston, SC; salinity values for Year 1 summer (red) and Year 2 (blue) are shown for each point.

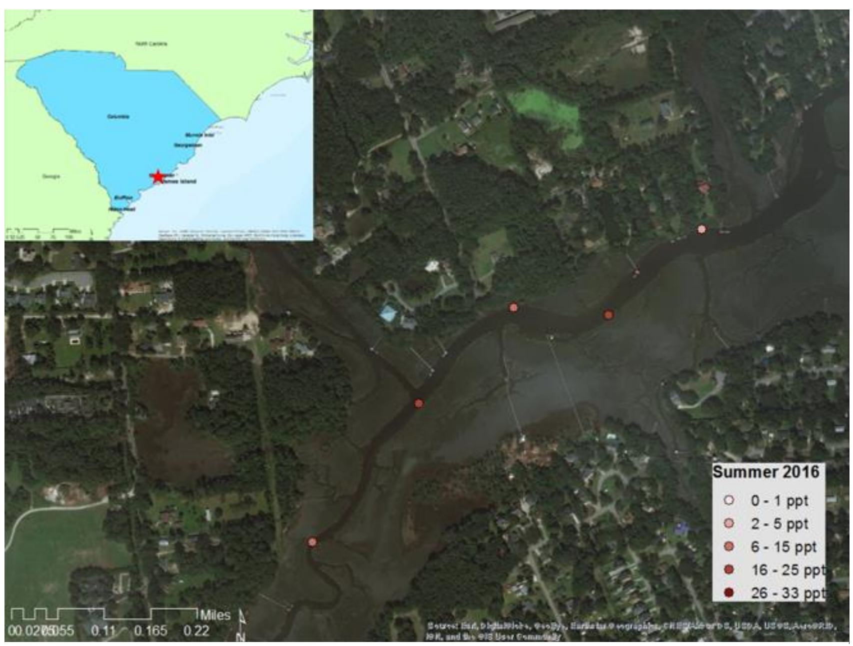


Figure C.13 Locations of sampling points at James Island located in a developed (urban) watershed in Charleston, SC; salinity values for Year 1 summer (red) are shown for each point.


Figure C.14 Locations of sampling points at Heyward Cove located in a developed (urban) watershed in Bluffton, SC; salinity values for Year 1 summer (red) are shown for each point.


Figure C.15 Locations of sampling points at Murrells HW located in a developed (urban) watershed in Murrells Inlet, SC; salinity values for Year 1 summer (red) are shown for each point.